LFV/LNV

S. XELLA – NIELS BOHR INSTITUTE

FOCUS ON ~ 100 GEV SCALE : TOP, W, Z DECAYS

- For sensitivity at lower energy scales (eg mu→ e ɣ), see earlier Snowmass Session

  https://snowmass21.org/rare/clfv
- Here we focus on ~ 100 GeV scale , on-shell weak bosons or top quark decays
- In this session, see also LFV in Higgs and heavier (BSM) reasonances decays talks.

- As for experimental apparatus, I focus on LHC , HL-LHC and FCC-ee because , for this energy regime, they constitute the two best possible avenues for the future for these studies at colliders for the coming ~20 years period.

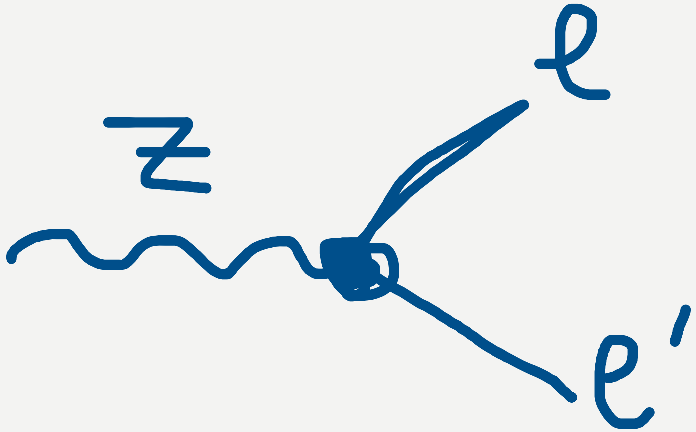
LFV/LNV

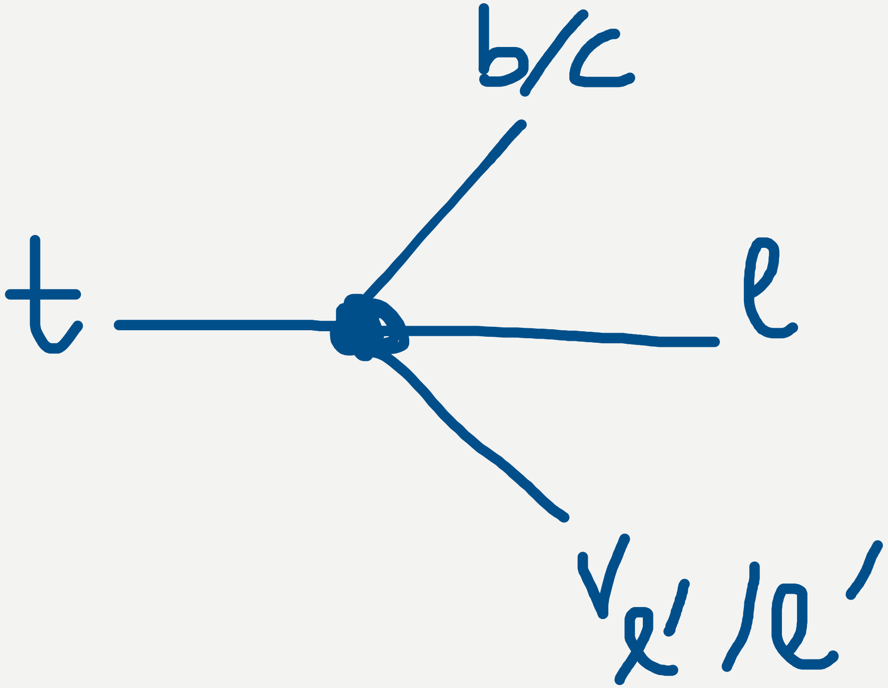
Lepton Flavour number = N leptons (flavour) – N anti-leptons (flavour)

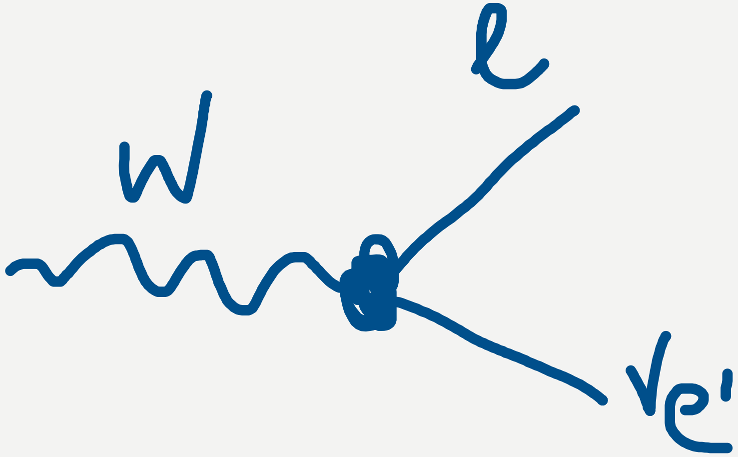
Lepton Number = N leptons – N anti-leptons

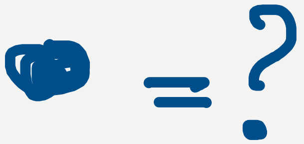
LFV = violation of Lepton Flavour number conservation

LNV= violation of Lepton number conservation





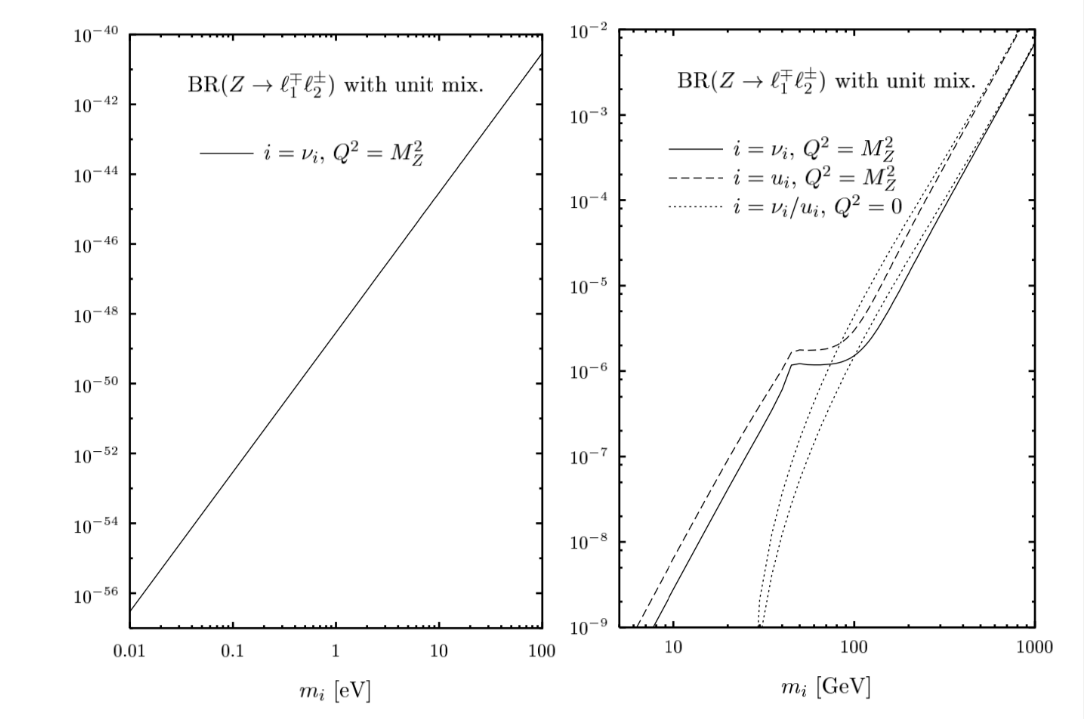




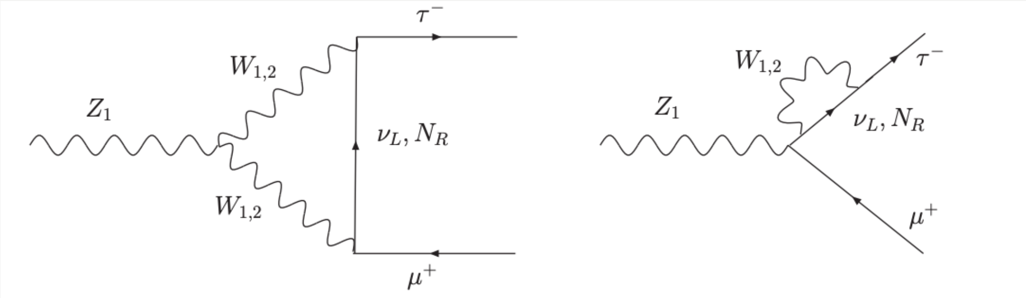
new physics

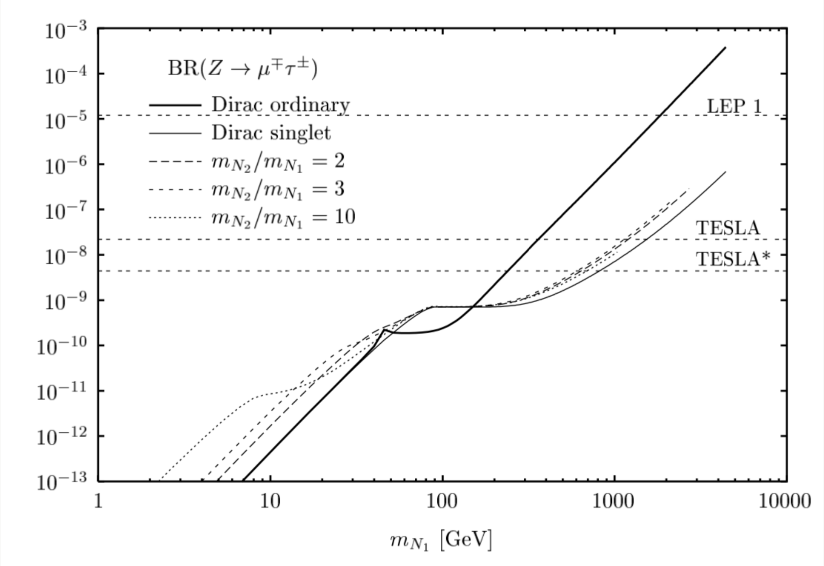
Experimental signatures focus of the talk : Decays of W, Z and top quark. Energy scale ~ 1-100 GeV

POSSIBLE PHYSICS BEHIND LFV : Z→LL'



Size of the BR for one additional heavy neutrino generation i of Dirac nature in the small and large neutrino mass regions (left), and for two additional Majorana neutrinos (bottom)



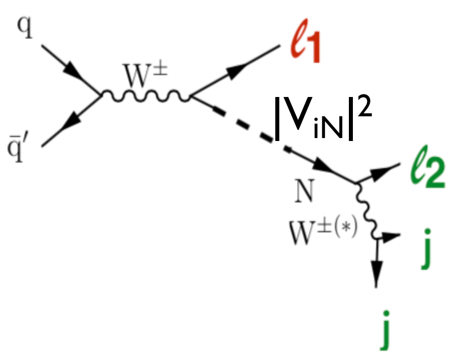


[1,10]

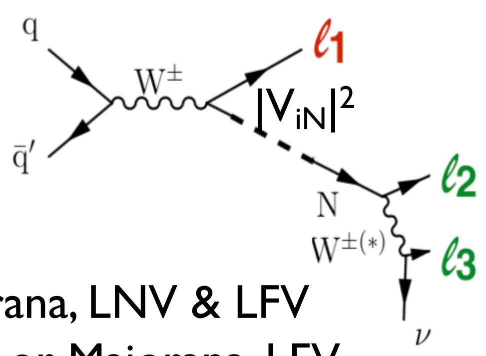
BR are very small. Precision is key to investigate new Physics in LFV processes

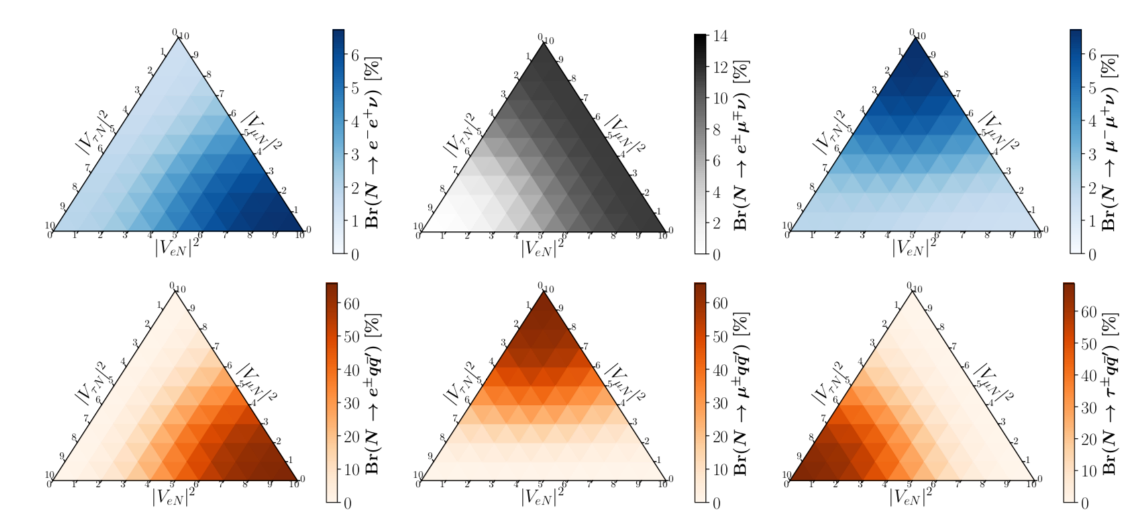
POSSIBLE PHYSICS BEHIND LFV/LNV : W→ LL'X

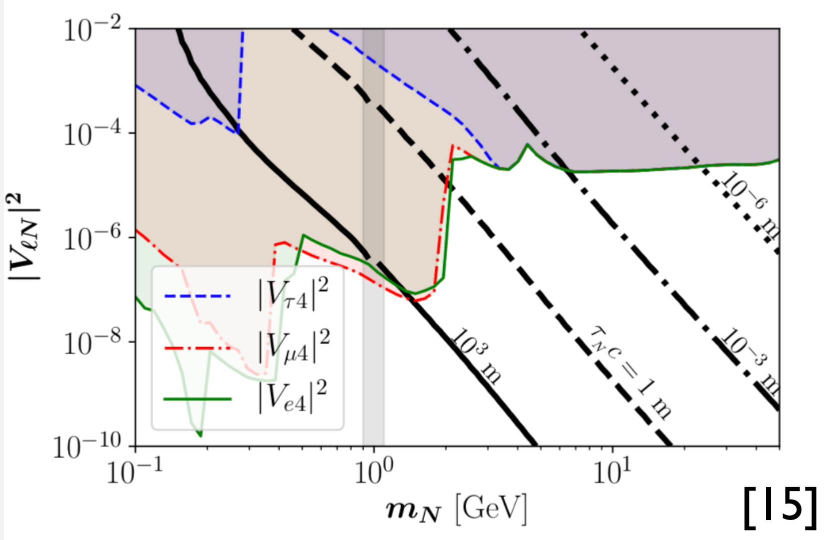
$$\sigma(pp \to W)\cdot\mathcal{B}(W \to \ell N) = \overbrace{\sigma(pp \to W)\cdot\mathcal{B}(W \to \ell\nu)}^{\text{20 nb}}\,|V_{iN}|^2 \left(1-\frac{m_N^2}{m_W^2}\right)^2\left(1+\frac{m_N^2}{2m_W^2}\right)$$ [16]



l_1	l_2	
e+	e+	Majorana, LNV & LFV
e+	mu-	Dirac or Majorana, LFV







[15]

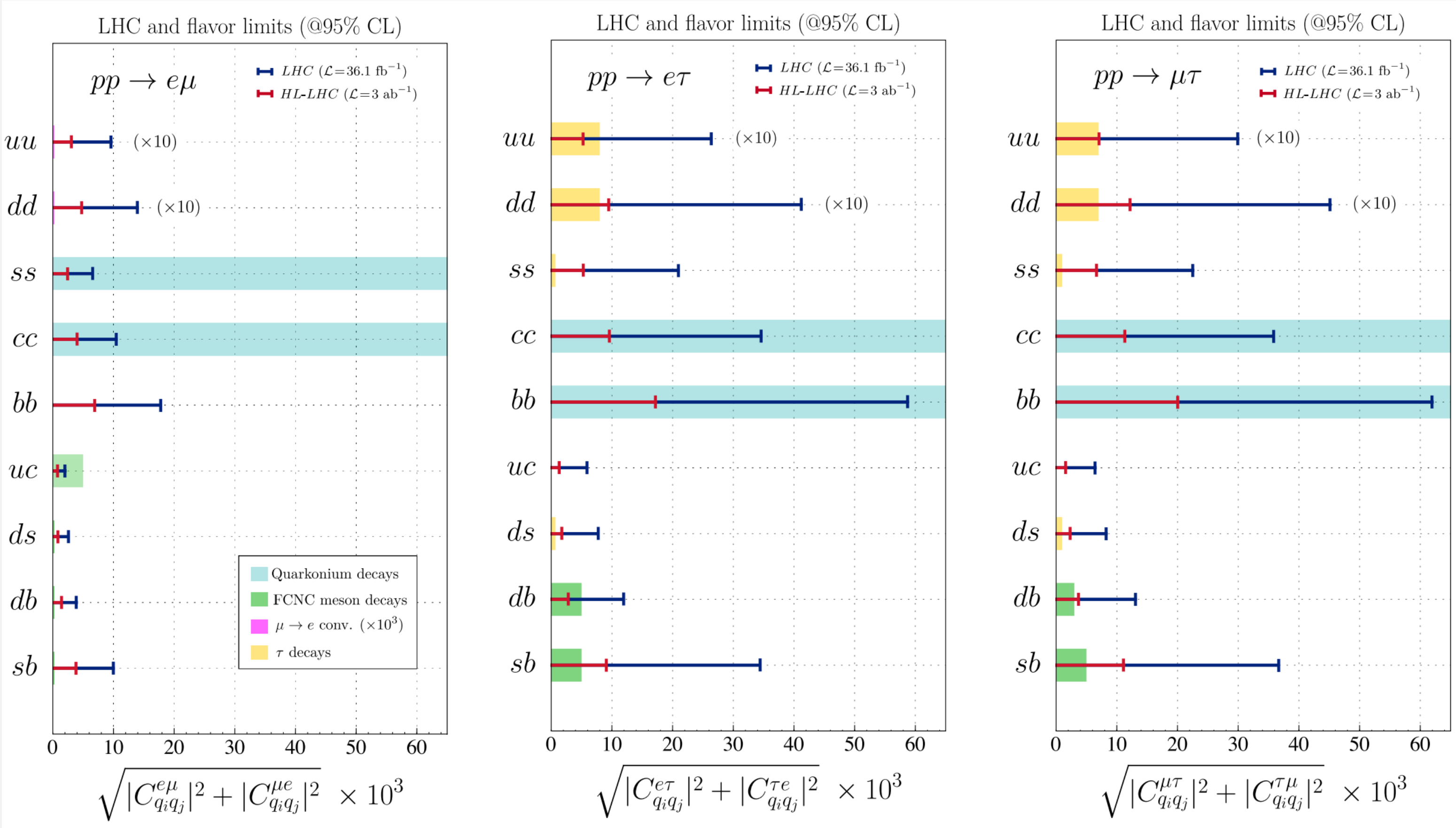
the ratio between different final state flavors will provide information on the mixing ratios

[15]

$$\tau \propto \sum_i |V_{iN}|^{-2} m_N^{-5}$$

COMPLEMENTARITY OF HIGH AND LOW ENERGY EXPERIMENTS

LFV high mass tails of two leptons l_1 l_2 at the LHC or HL-LHC ,
and complementarity with results from low mass flavor physics experiments

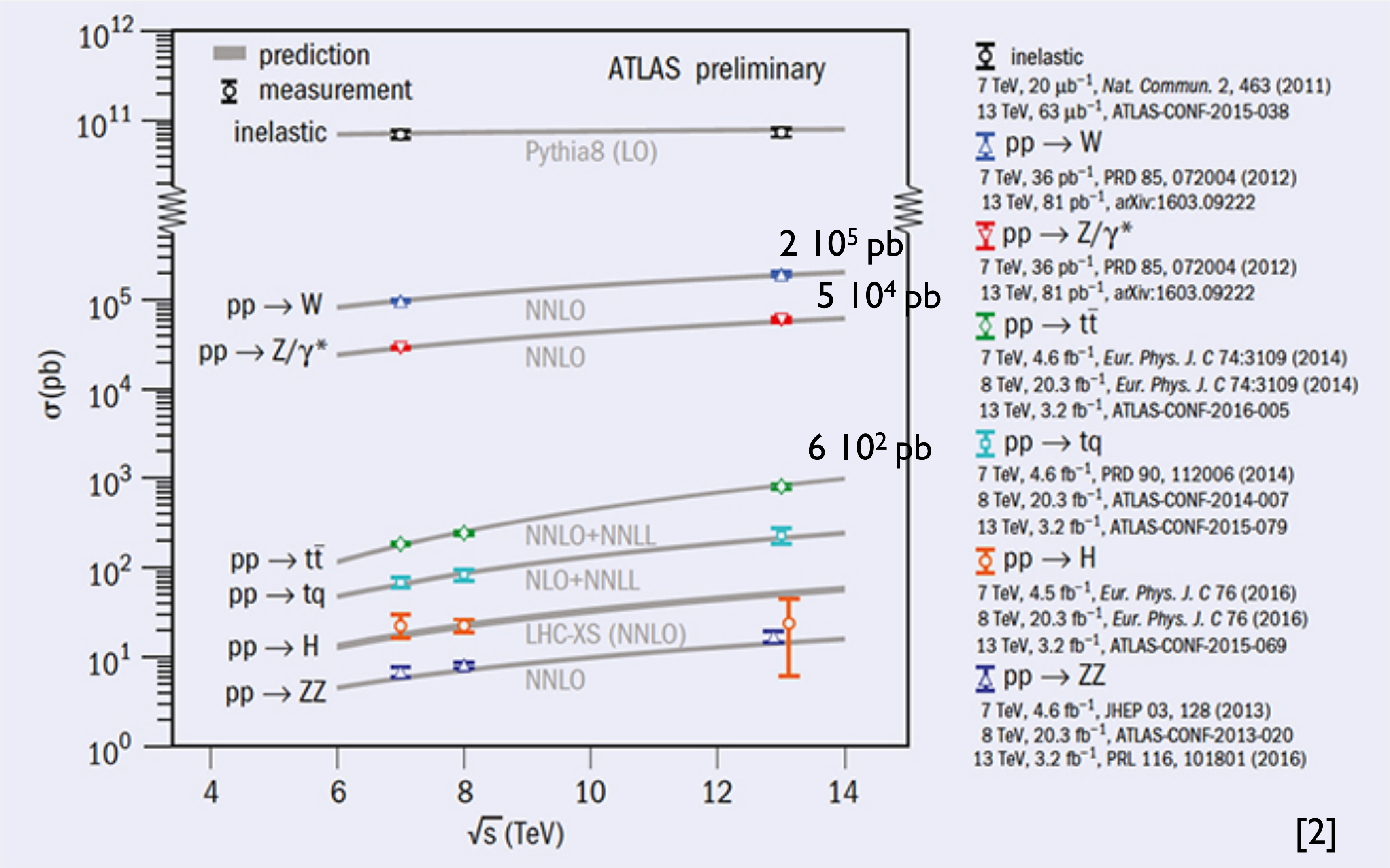


[22]

EFT with generic semileptonic dimension-6 operators.
C^{ijkl} = Wilson effective coefficients

quarkonium decays (cyan),
μN → eN (magenta),
FCNC meson decays (green)
and LFV τ -decays (yellow).

WHY SPECIFICALLY W,Z,TOP DECAYS?



[2]

Run 1+2+3 :
300 fb^{-1}

1.5 10^{10} Z's
6 10^{10} W's
2 10^{8} top's

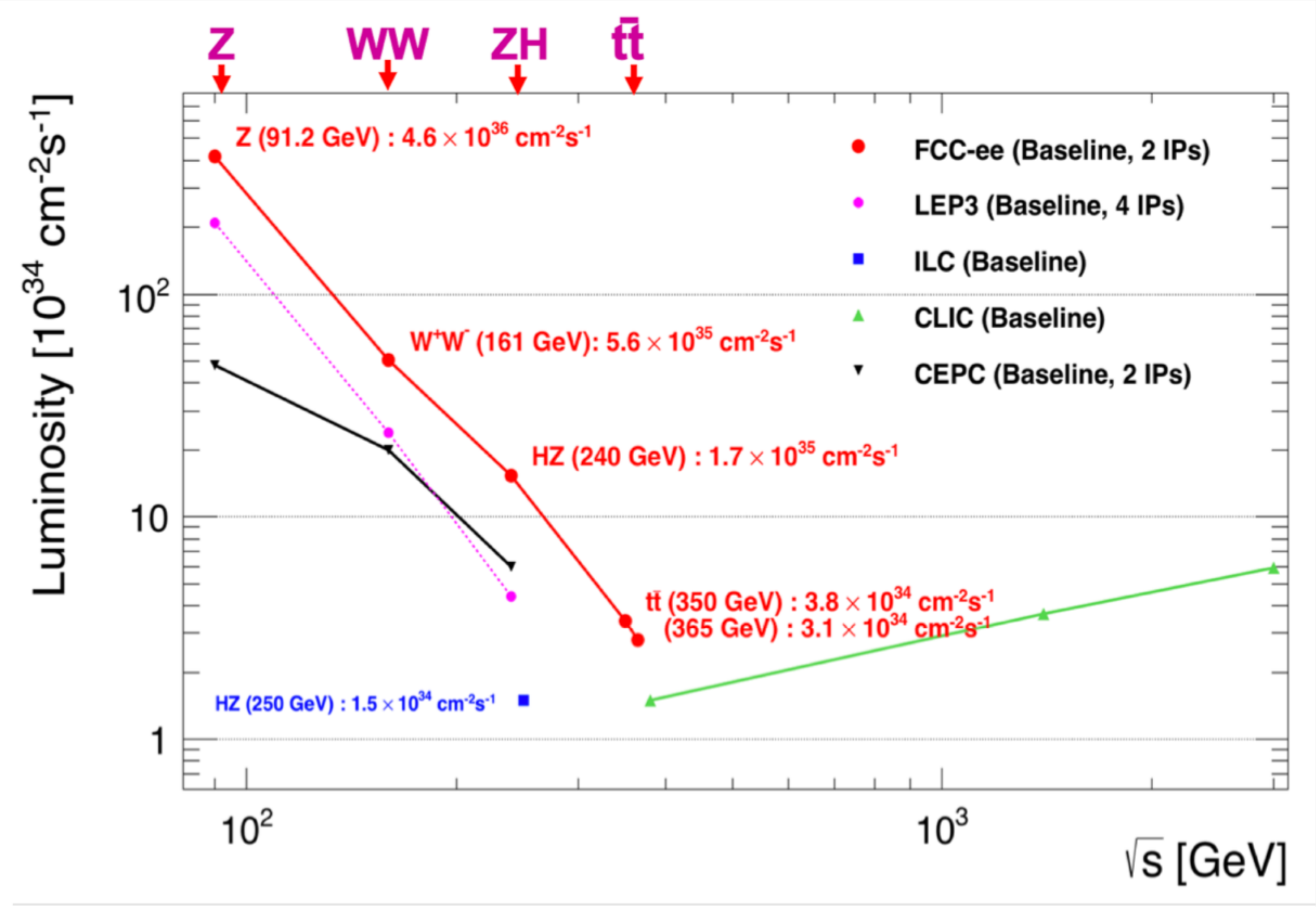
End of HL-LHC :
3000 fb^{-1}

Lots of events where to search for LFV effects.

High backgrounds and less kinematic constraints limit the precision

→ Resort to sophisticated analysis algorithms (eg ML) helps

WHY SPECIFICALLY W,Z,TOP DECAYS?



FCC-ee , if constructed, will provide:

$5\ 10^{12}$ ee → Z
10^{8} ee → WW
10^{6} ee → tt

in a very clean environment, and with strong kinematic constraints imposable. Even with less events than LHC, the precision is often better than LHC

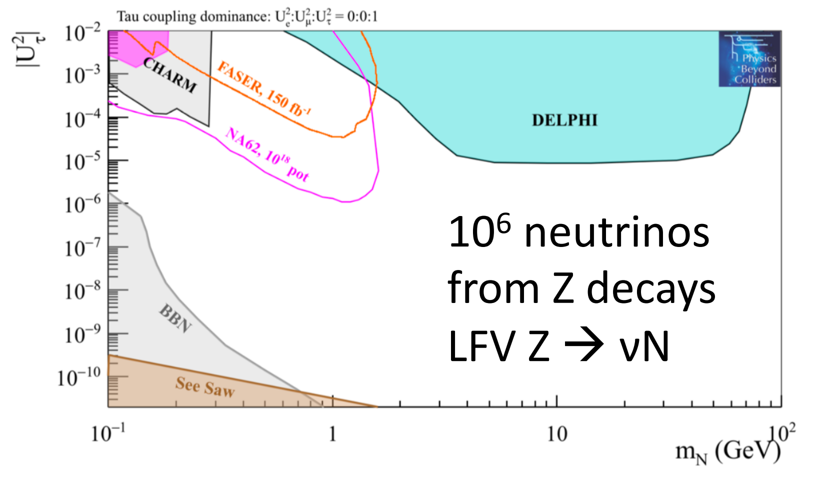
… and precision is what counts when trying to spot LFV effects

CURRENT EXPERIMENTAL PRECISION

Until 2015, precision still driven by LEP results using Z's

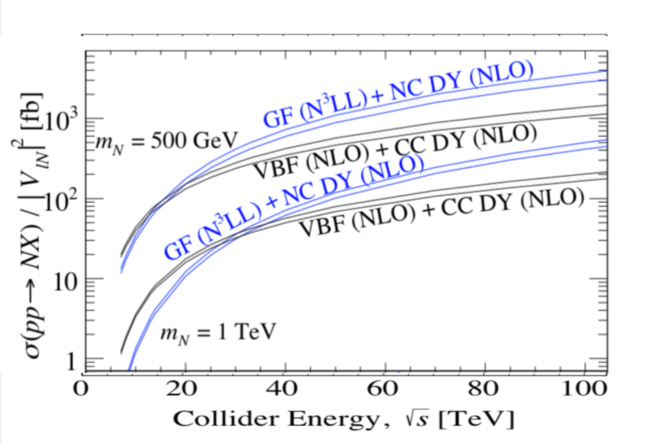
$$\mathrm{BR}(Z \to e\mu) < 1.7 \times 10^{-6}$$
$$\mathrm{BR}(Z \to e\tau) < 9.8 \times 10^{-6},$$
$$\mathrm{BR}(Z \to \mu\tau) < 1.2 \times 10^{-5}$$

[3,4]



[5]

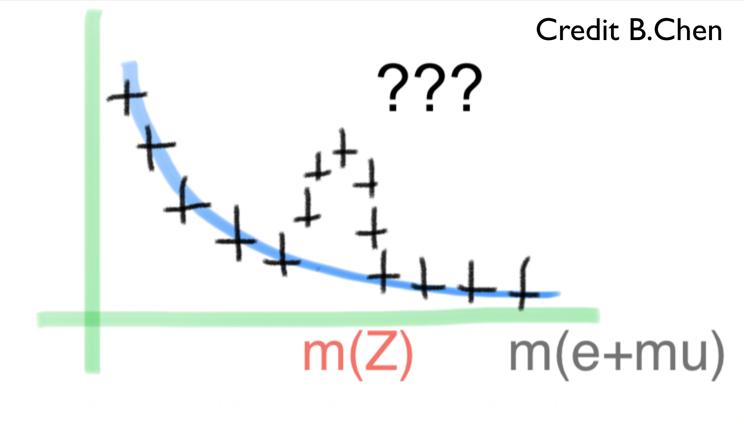
Or top decays at HERA $\mathrm{BR}(t \to l_1 l_2 q) < 10^{-3}$ [9]

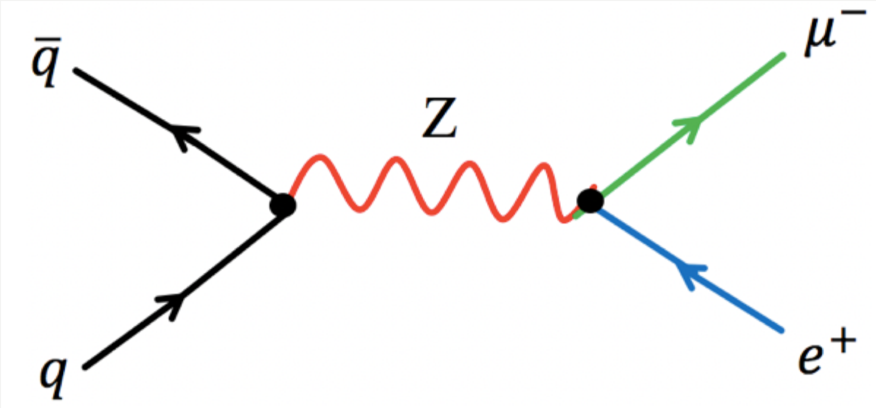


But LHC is catching up and superseeding these results now.
See the following slides.
Higher energies & luminosity pp , or Higher intensity e+ e- , beams at FCC will improve tremendously on precision

For pictures of the experimental apparata check the backup slides

ATLAS/CMS : LFV Z → E MU





experiment	N. Of Zs	UL (95% CL)
OPAL	10^{6}	17 10^{-7}
ATLAS 8 TeV	8 10^{8}	7.5 10^{-7}
CMS 8 TeV	8 10^{8}	7.3 10^{-7}

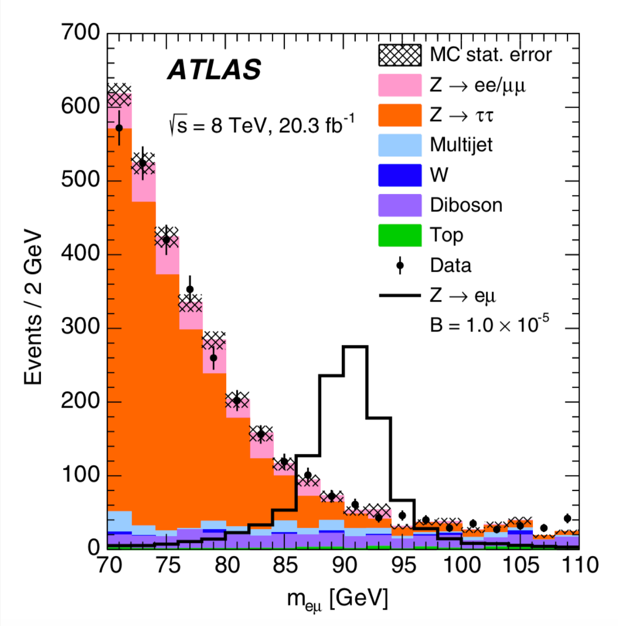
Already improves considerably LEP sensitivity with 20 fb^{-1}

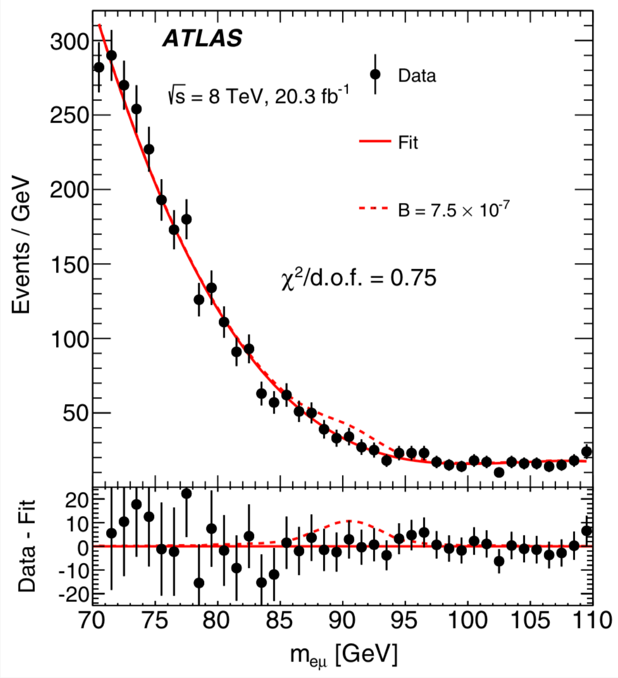
Updates with Run2 statistics (+140 fb^{-1}) , and analysis improvements, on the way

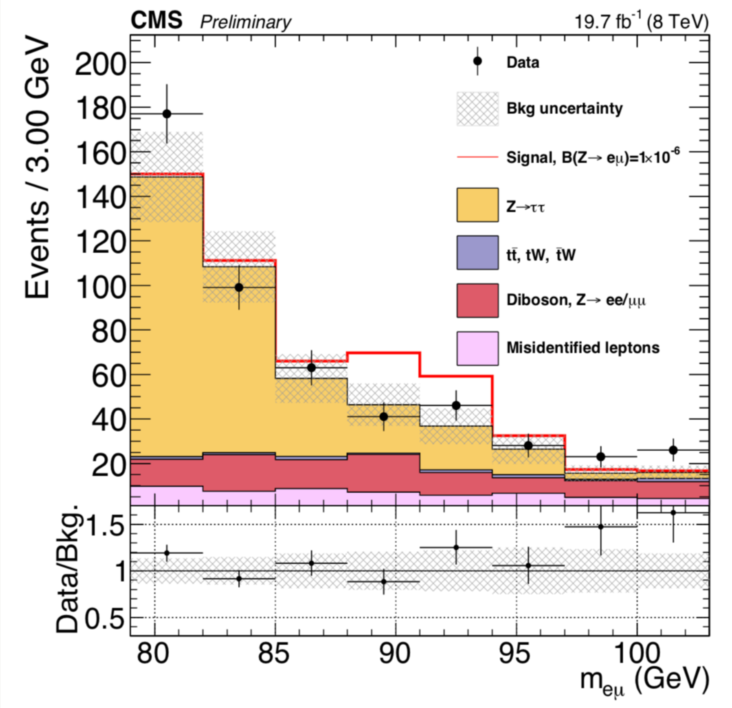
ATLAS:
Data driven background estimation, using sidebands.
Biggest backgrounds

- Z → τ τ → e μ + Missing energy
- Z → μ μ where one μ fakes e signature due to decay, ɣ radiation, ECAL deposits

Dominant uncertainty is statistics from PDF for backgrounds used in the fit







[17,18]

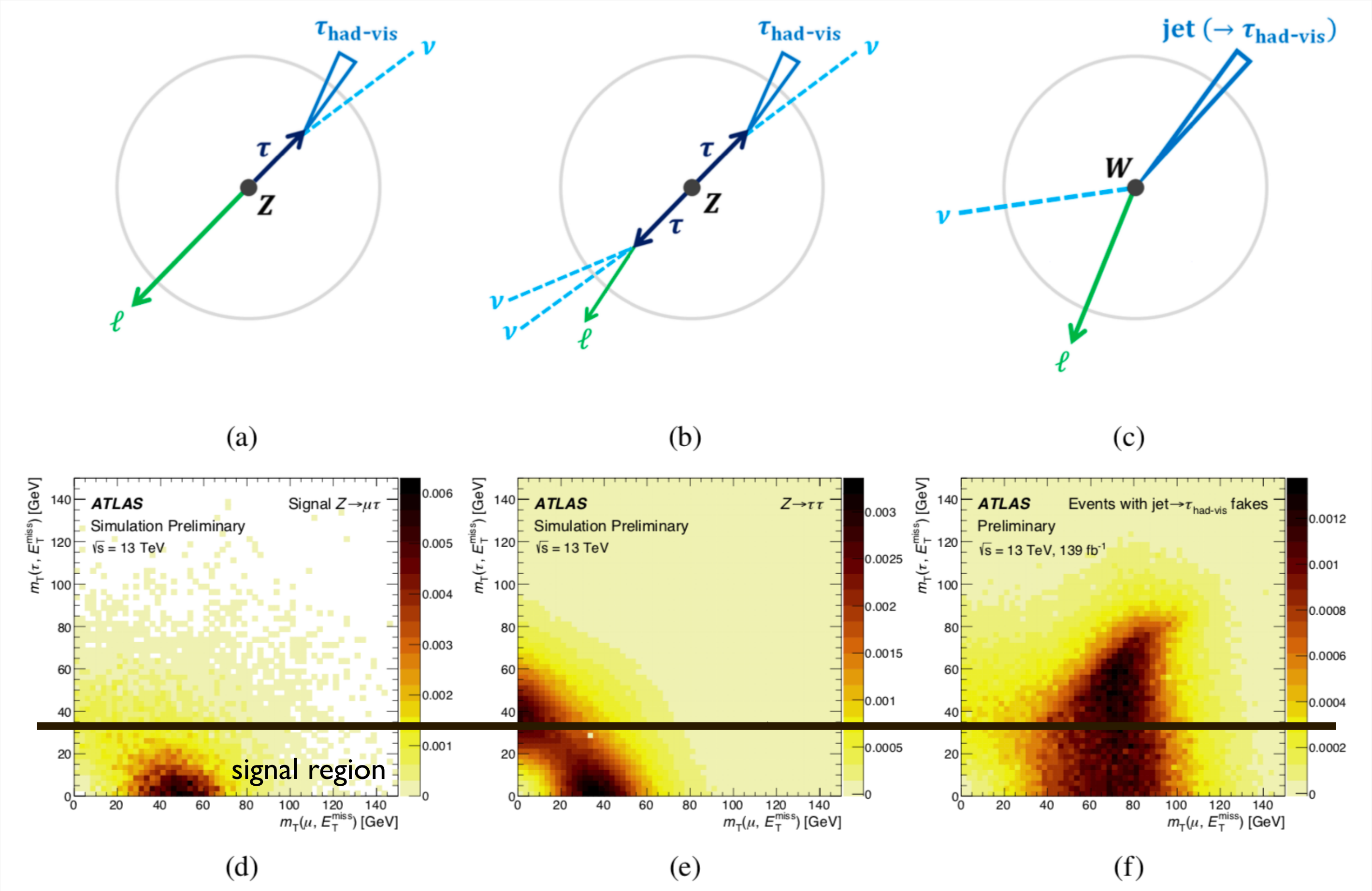
CMS

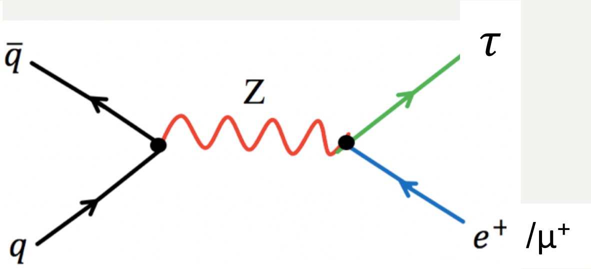
Source	Uncertainty Background	Uncertainty Signal
Luminosity	2.6%	2.6%
Pileup	3.3%	0.8%
Trigger	0.3%	0.5%
Muon Id	0.5%	0.8%
Muon p_T scale	2.9%	0.2%
Muon p_T resolution	0.4%	0.1%
Electron Id	0.5%	0.8%
Electron energy scale	3.1%	1.1%
Electron energy resolution	0.3%	0.4%
Jet energy scale	0.2%	< 0.1%
Jet energy resolution	< 0.1%	< 0.1%
E_T^{miss}	0.6%	2.2%
Dilepton p_T	0.4%	1.1%
PDF	1.0%	1.0%
Limited number of simulated events	10.6%	1.2%
Normalization (Tab. 1)	6.8%	3.3%

Slightly different approach but similar precision

Statistics limited measurement

ATLAS : LFV Z → E TAU/MU TAU



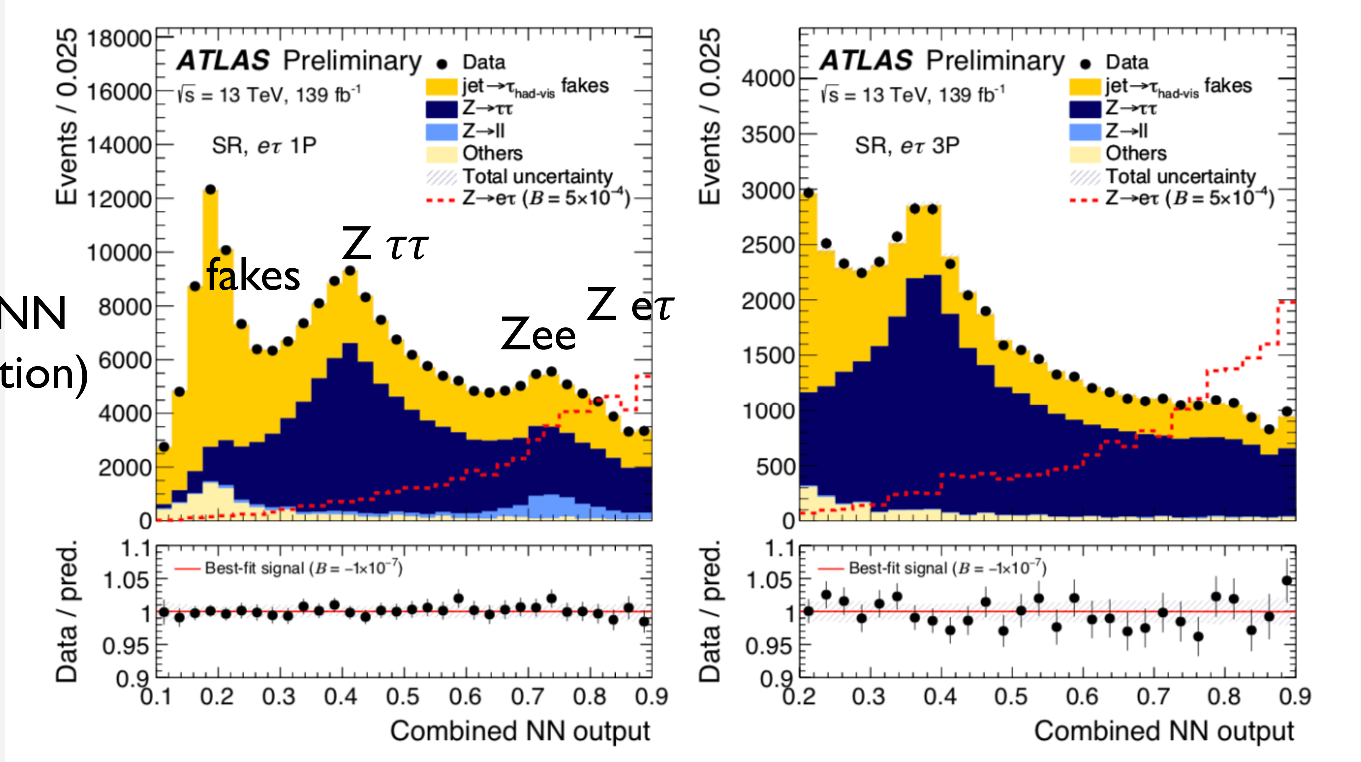


Irreducibile background from Z→ τ τ

Need to use all possible available informations in the event to distinguish signal from background

Recurrent neural network (deep neural network) used as final observable, as more powerful to extract a signal

Hadronic 1-prong tau decay (recursive NN also for tau identification)



Hadronic 3-prong tau decay (recursive NN also for tau identification)

[19]

Variable	Description
$p_z(\ell)$	z-component of the light lepton momentum.
$E(\ell)$	Energy of the light lepton.
$p_x(\tau_{\text{had-vis}})$	x-component of the $\tau_{\text{had-vis}}$ momentum.
$p_z(\tau_{\text{had-vis}})$	z-component of the $\tau_{\text{had-vis}}$ momentum.
$E(\tau_{\text{had-vis}})$	Energy of the $\tau_{\text{had-vis}}$.
$E_{\text{T}}^{\text{miss}}$	The missing transverse momentum.
$m_{\text{vis}}(\ell,\tau)$	The visible mass: the invariant mass of the ℓ–$\tau_{\text{had-vis}}$ system.
$m_{\text{coll}}(\ell,\tau)$	The collinear mass: the invariant mass of the ℓ–$\tau_{\text{had-vis}}$–ν system, where the ν is assumed to have a momentum that is equal in the transverse plane to the measured $E_{\text{T}}^{\text{miss}}$ and collinear in η with the $\tau_{\text{had-vis}}$ candidate.
$m(\ell,\tau\text{ track})$	The invariant mass of the light lepton and of the track associated to the $\tau_{\text{had-vis}}$ candidate (Only used by the $Z\to\ell\ell$ classifier).
$\Delta\alpha$	A kinematic discriminant sensitive to the different fraction of τ four-momentum carried by neutrinos in signal and background [28].

Low level variables (in in a boosted and rotated frame of reference where the transverse momentum of the l–τ – Emiss system is zero and the Emiss is aligned with the positive x-axis, helps to remove some dof)

High level variables, in lab frame.
M-coll is most important and
m(l, track) is good for killing Z→μμ
fakes background)

[19]

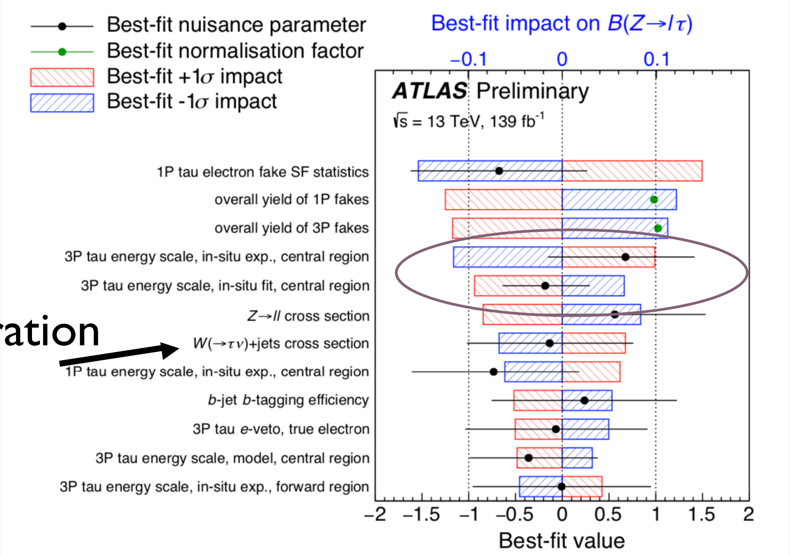
Experiment, polarisation assumption	Observed (expected) upper limit on $\mathcal{B}(Z \to \ell\tau)$ [$\times 10^{-6}$] $e\tau$	$\mu\tau$
ATLAS Run 2, unpolarised τ	8.1 (8.1)	9.9 (6.3)
ATLAS Run 2, left-handed τ	8.2 (8.6)	9.5 (6.7)
ATLAS Run 2, right-handed τ	7.8 (7.6)	10 (5.8)
ATLAS Run 1, unpolarised τ [53]		17 (26)
ATLAS Run 1 and Run 2, unpolarised τ		9.5 (6.1)
LEP OPAL, unpolarised τ [10]	9.8	17
LEP DELPHI, unpolarised τ [11]	22	12

Beats LEP sensitivity !

Uncertainty	Impacts on signal branching fraction [$\times 10^{-6}$] $e\tau$	$\mu\tau$
Statistical	±3.5	±2.8
Systematic	±2.3	±1.6
Tau	±1.9	±1.5
Energy calibration	±1.3	±1.4
Jet rejection	±0.3	±0.3
Electron rejection	±1.3	
Light lepton	±0.4	±0.1
E_T^{miss}, jet and flavour tagging	±0.6	±0.5
Z background modelling	±0.7	±0.3
Luminosity and other minor backgrounds	±0.8	±0.3
Total	±4.1	±3.2

Still statistics dominated

Tau energy calibration can be improved too with more data



HL-LHC LFV Z

- No specific studies for these Z decays channels included in the Report from Working Group 4 on "Opportunities in Flavour Physics at the HL-LHC and HE-LHC" [21]. Probably because trivial to extrapolate.
- For LFV Z decays, statistics increase and improvements in energy calibration can buy some space.
- The analysis method is already quite sophisticated using RNN both in identification of taus and in event selection and signal extraction (For Z →eμ moving to BDT).
- Additional Improvements can come from
  - Adding Z→ lep tau_lep channel (ongoing)
  - HL-LHC acceptance of tracking detectors increases
  - More lumi→ more stats , limit improves by 1/√lumi ~ 4 by HL-LHC wrt Run1+Run2
- We probably arrive at some ~ 10^{-7} for Z-> lτ and 10^{-8} for Z →eμ
- Interesting for quite some time still!

FCC-EE: LFV Z->EMU

[25,26]

The event topology is a Z decaying to an unlike pair of leptons of different flavour and opposite charge, back to back, with the beam energy. So simple!

Impressive momentum resolution of FCC-ee detectors and Z mass constraint from extremely well known beam energy are very powerfull
→ Signal will be a delta function on top of a falling background tail from Z→ $\tau\,\tau$ → e μ + neutrinos
So Z → $\tau\,\tau$ is a negligible background

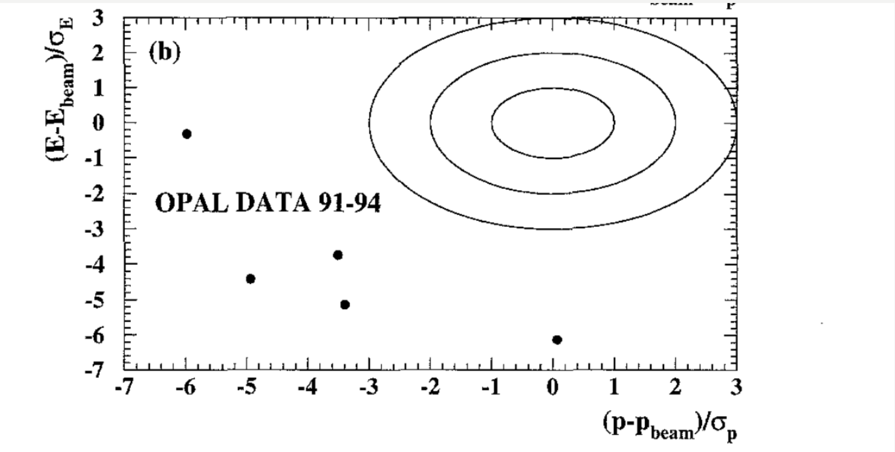


Fig. 4. Difference between the total electromagnetic cone energy of the electron candidates and the beam energy divided by the error on the energy versus the difference between the total charged track cone momentum of the muon candidates and the beam momentum divided by the error on the momentum after the cuts for the eμ selection described in the text. Shown are the one, two and three standard deviation contours. In **(a)** the

Problematic background:
Z→μμ with bremsstrahlung of muon in the material of the electromagnetic calorimeter (ECAL)→ looks e
NA62 measurement : expect 3 10^{-7} Z →μμ background due to this.
Situation is better due to:
ECAL energy resolution (cut on E deposit in ECAL) and segmentation (shape of shower)
dE/dx (separation muon vs electron at 45 GeV ~ 2-3 sigma)
→ **10^{-8} doable, better than 10^{-9} if using dE/dx likely**

FCC-EE: LFV Z->ETAU/MUTAU

[25,26]

Search for a clear tau decay in one hemisphere recoiling against a beam momentum electron or muon

Clear tau decay: avoid Z→ ee or μμ background. Focus eg on specific exclusive modes as $\tau \rightarrow \rho\nu \rightarrow \pi\, \pi^0\, \nu$, or 3-prong decays

e/μ from τ in Z→ $\tau\,\tau$ background will have distribution with endpoint p_{beam}
The density of events close to the endpoint depends on τ polarization

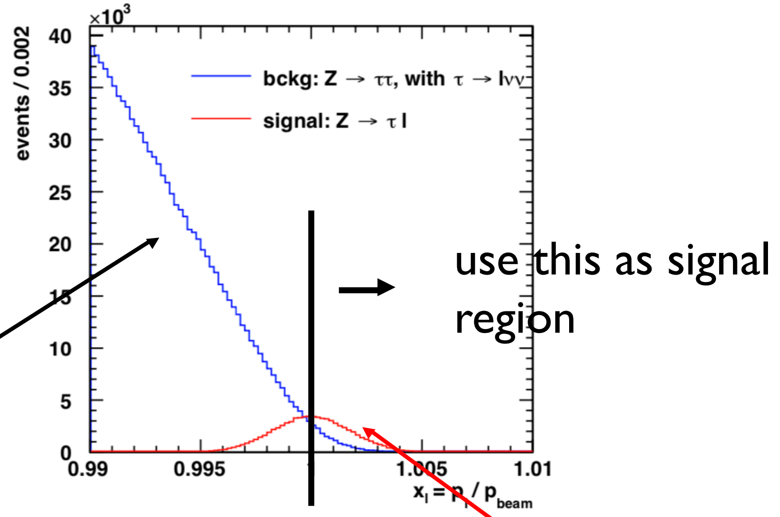


Figure 3: FCC-ee search for the lepton flavour violating decay $Z \to \tau\ell$, $\ell = e, \mu$. Momentum distribution of the final state lepton ℓ for the signal (red) and for the background from $Z \to \tau\tau$, with $\tau \to \ell\bar{\nu}\nu$ (blue). The shown momentum resolution of 1.8×10^{-3} results from the combination of the spread on the collision energy (0.9×10^3) and the detector resolution (1.5×10^{-3}). For illustration, the LVF branching fraction is set here to $\mathcal{B}(Z \to \tau\ell) = 10^{-7}$.

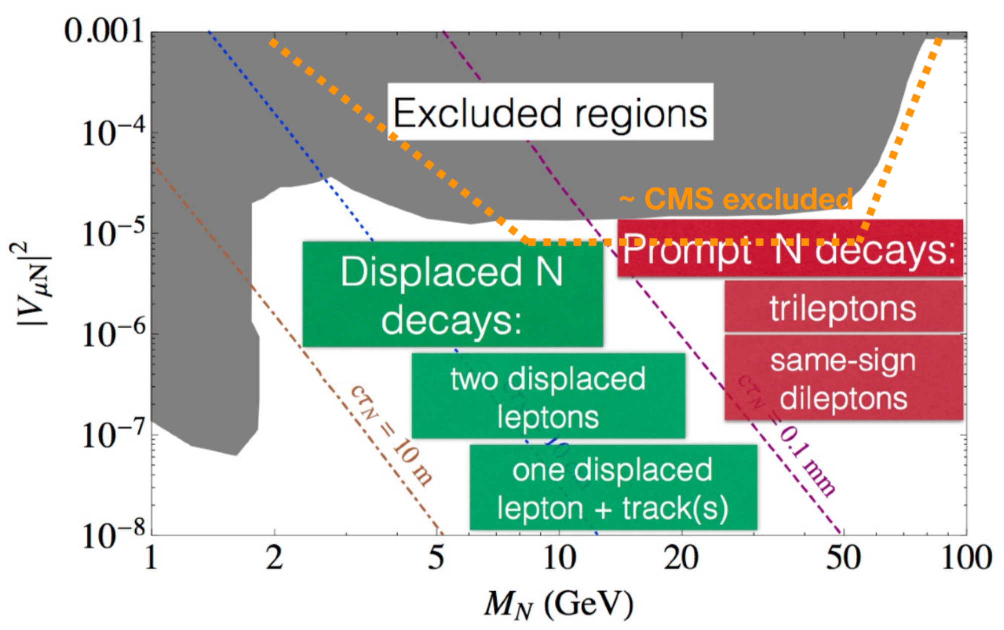
sensitivity down to BRs of 10^{-9}

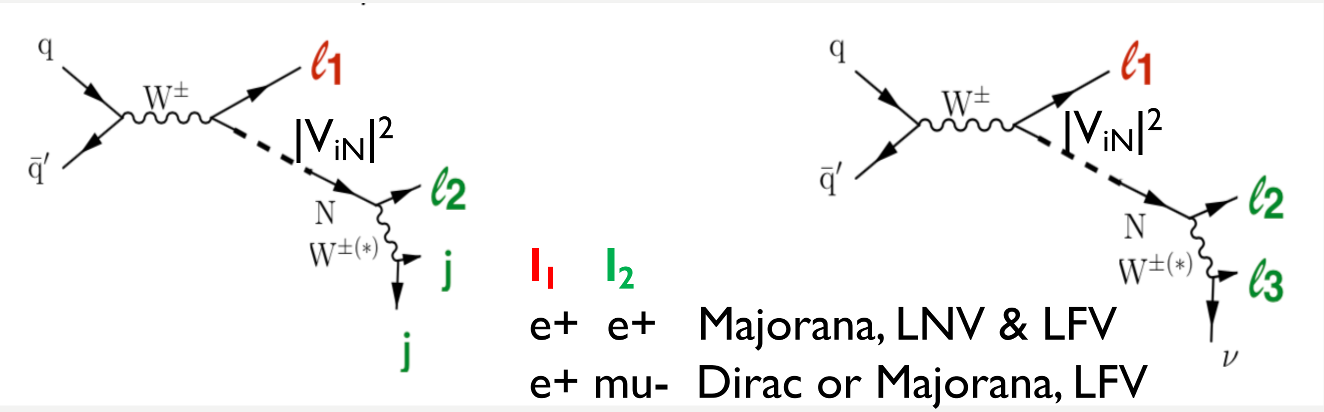
Scales linearly with momentum resolution

LFV/LNV W DECAYS

Depending on the nature of these heavy neutral leptons (HNL), decays can conserve or violate the lepton number

- Dirac: lepton number conserved (LNC) —> l_1 and l_2 OS
- Majorana: lepton number conserved (LNC) or violated (LNV) (LNV/LNC ratio is model dependent)
  LNC: l_1 and l_2 OS
  LNV: l_1 and l_2 SS





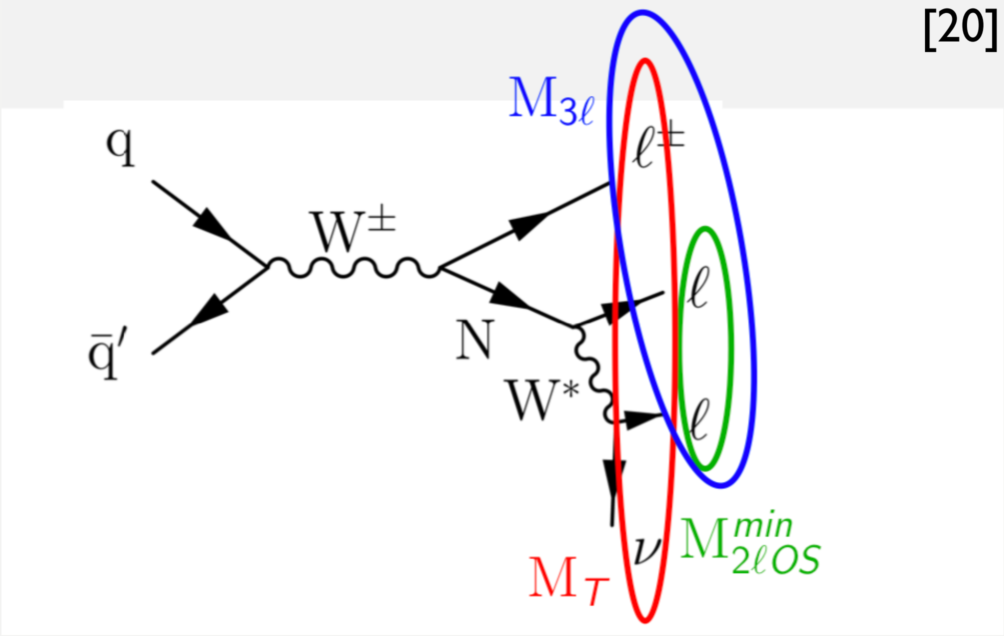
Interesting to explore all flavour combinations (to understand mixing active-sterile), and SS + OS processes to test nature of neutrinos

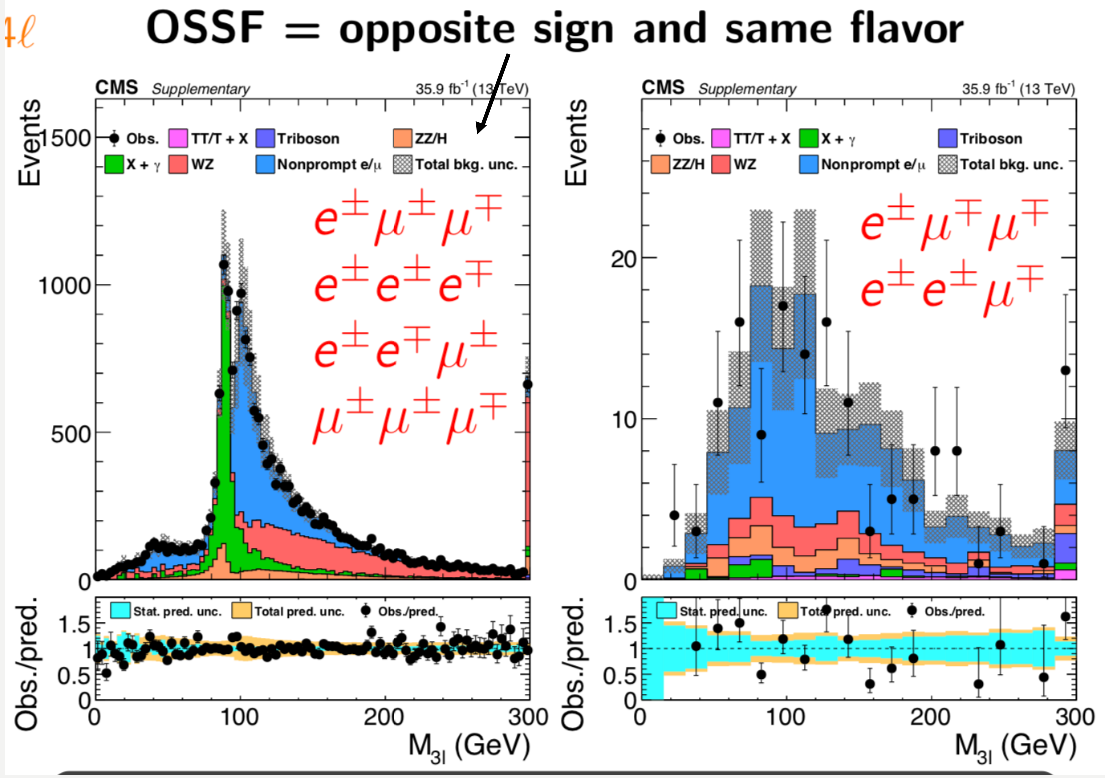
CMS

[20]

Search strategy based on

- M_{min} (2lOS), proxy for m_N
- M_T , very high for high m_N
- M(3l), for background rejection

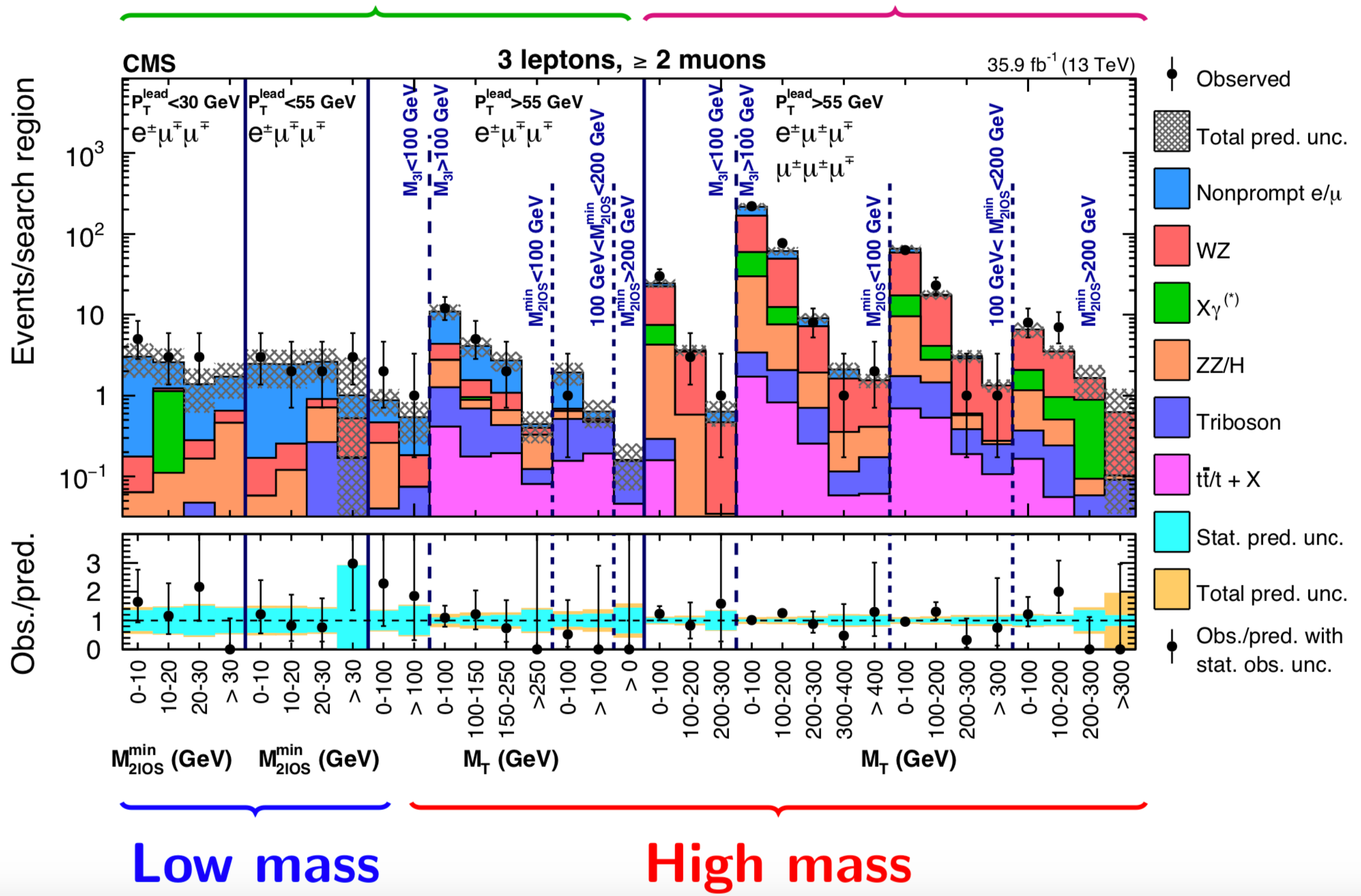




At low mass (M_N < M_W):
- only use events without OSSF (two orders of magnitude more background for events with an OSSF pair!)
- low PT thresholds
- categorize according to P_T leading

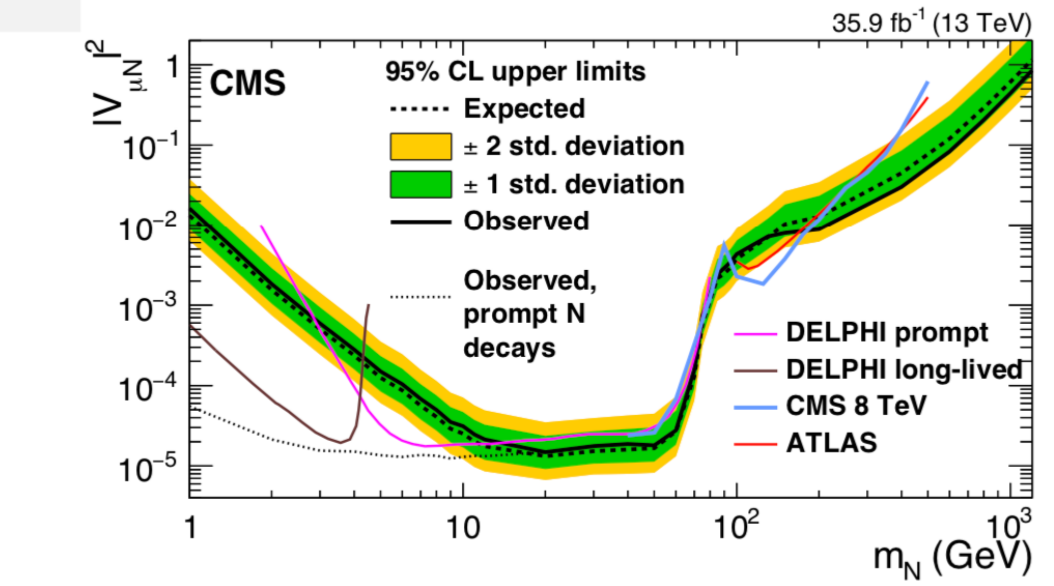
At high mass (M_N > M_W):
- Use all events
- high PT thresholds

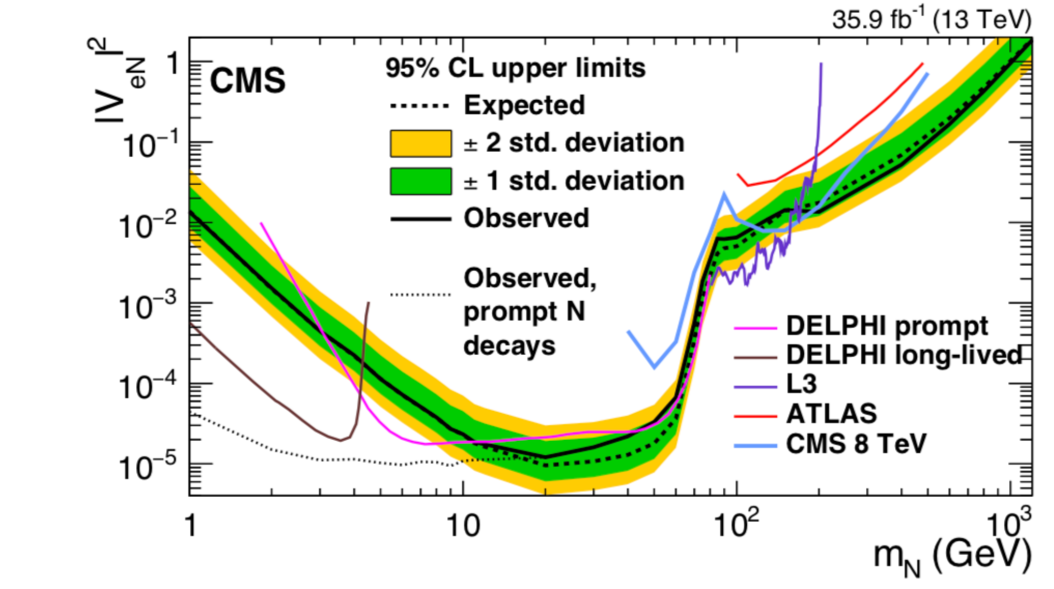
Signal regions



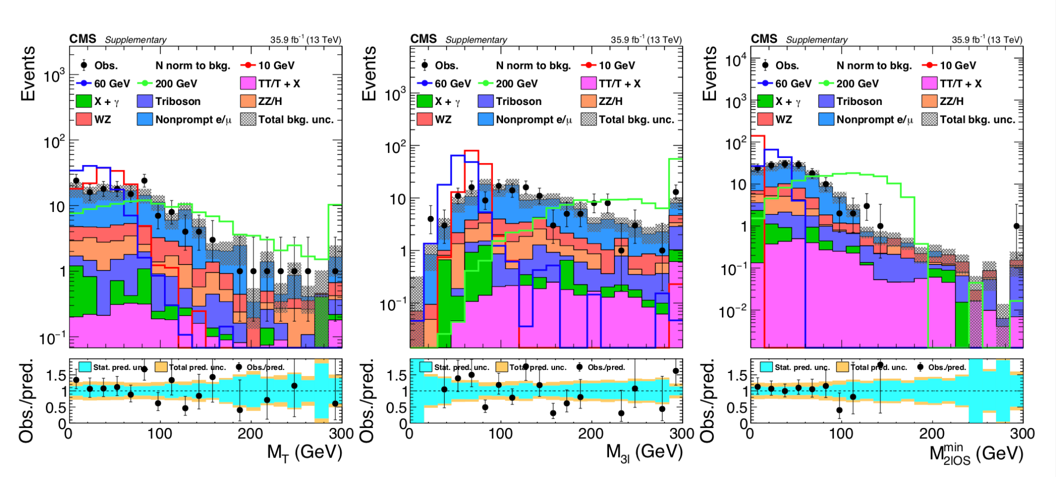
Exclusion limits

[7]





Low mass, no OSSF

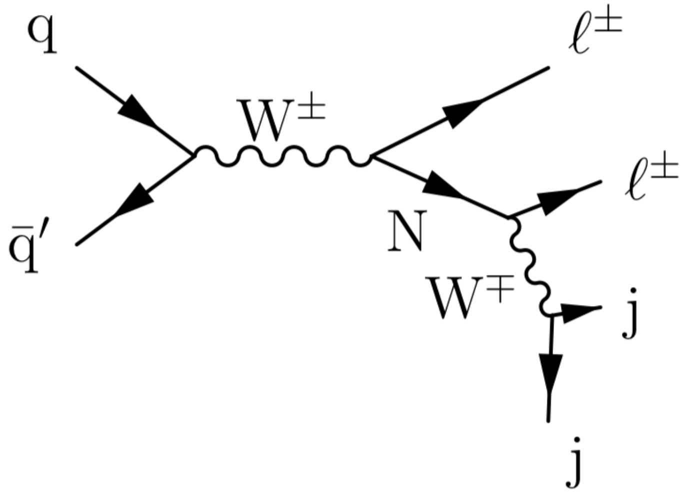


Totallty statistically limited!

Superseeds LEP experiments !
First result at hadron colliders for M_N < 100GeV
No focus on long lived N, requires special reconstruction

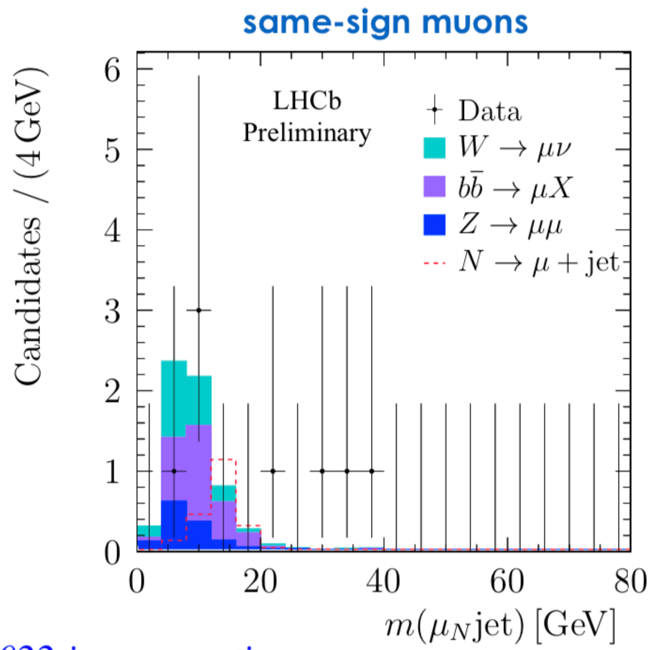
Prompt dimuon search: new result from LHCb

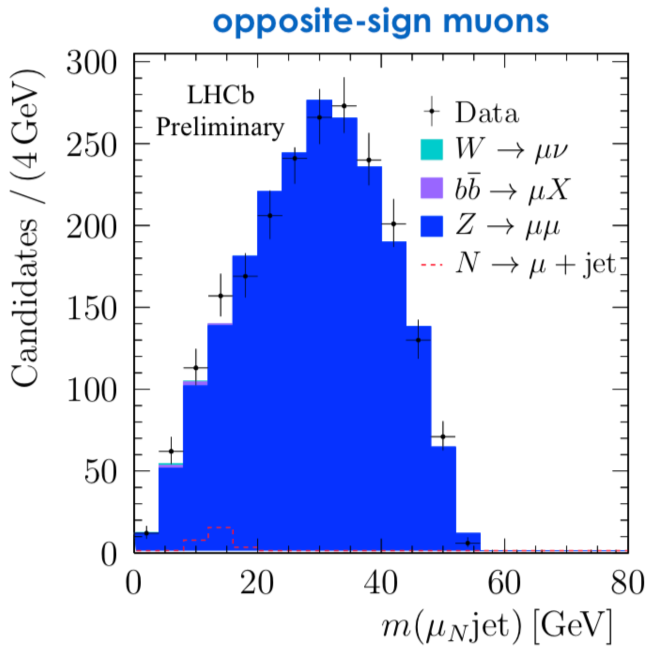
Dimuons (SS/OS) + 1 jet:



- jets are merged or 1 jet of 2 is out of acceptance
- allows to fully reconstruct N mass peak
- N can be light (jet $p_T > 10$ GeV)
- probe both **LNV** and **LNC** N decays

First search to look at the OS prompt muons (LNC decays)!

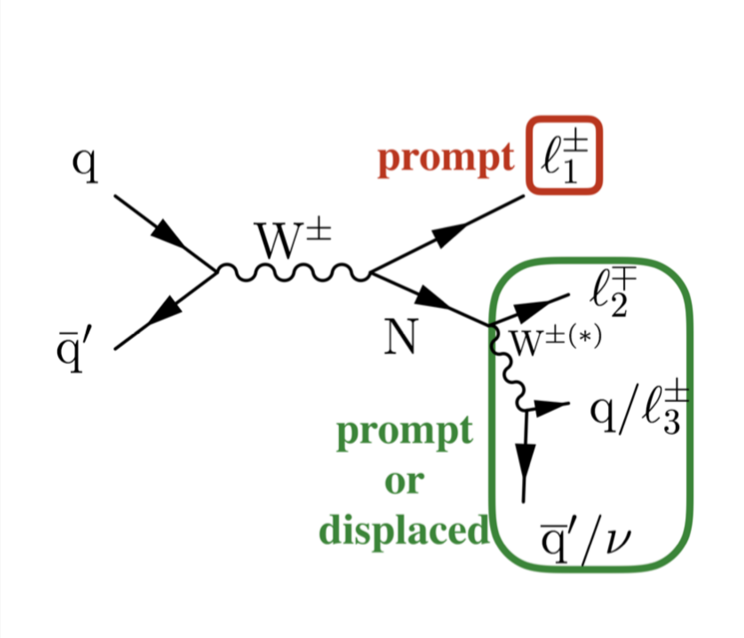


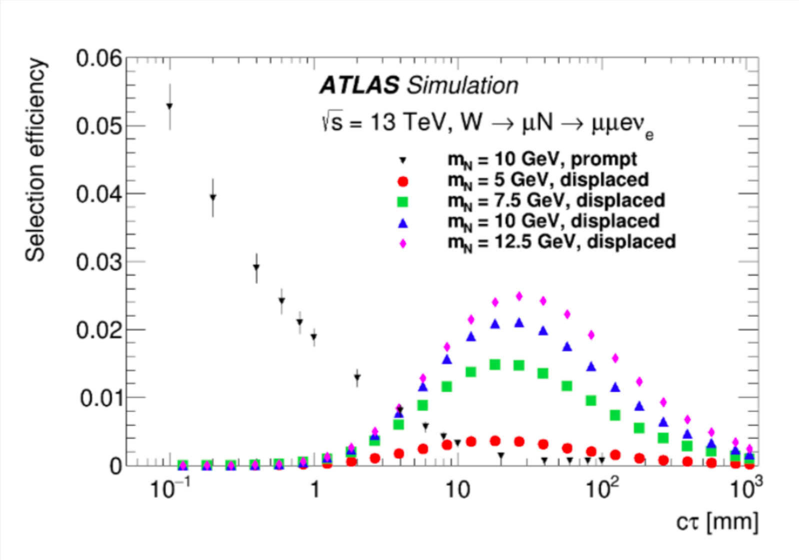


[23]

LHCb-PAPER-2020-022 in preparation

ATLAS





Displaced

Search strategy:

- OSSF or SSSF
- displaced μμ or μe

vertex: transverse displacement

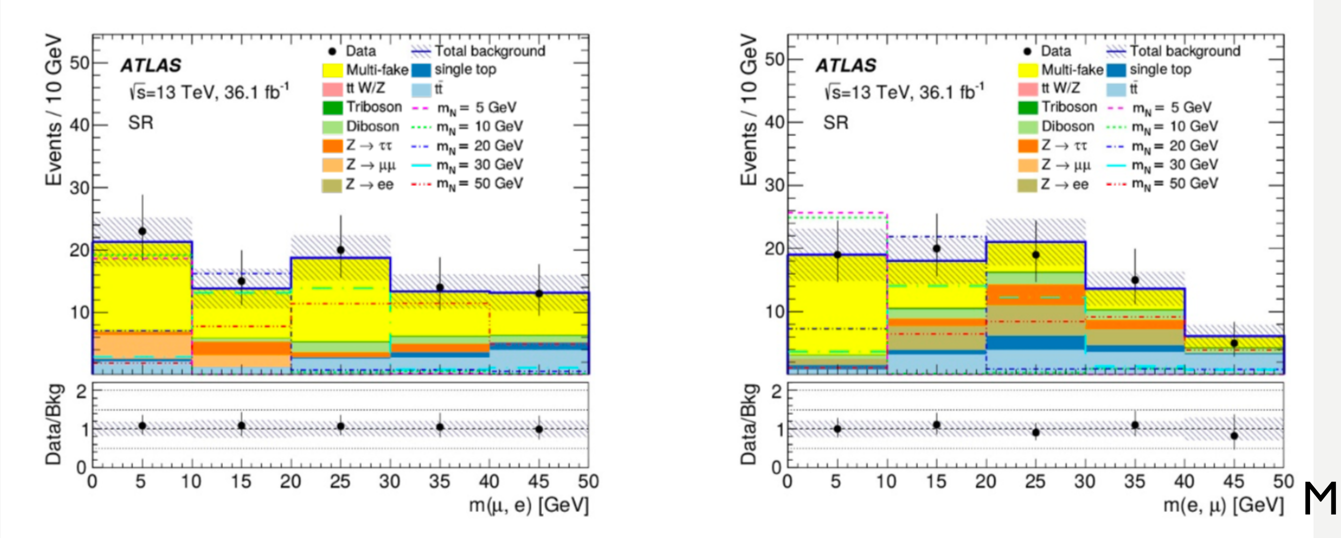
4 < rDV < 300 mm

Up to 1 m cτ !

Prompt

Search strategy :

- SSSF lepton pair
- M(3l) < 90 GeV
- Low MET
- No b-jets

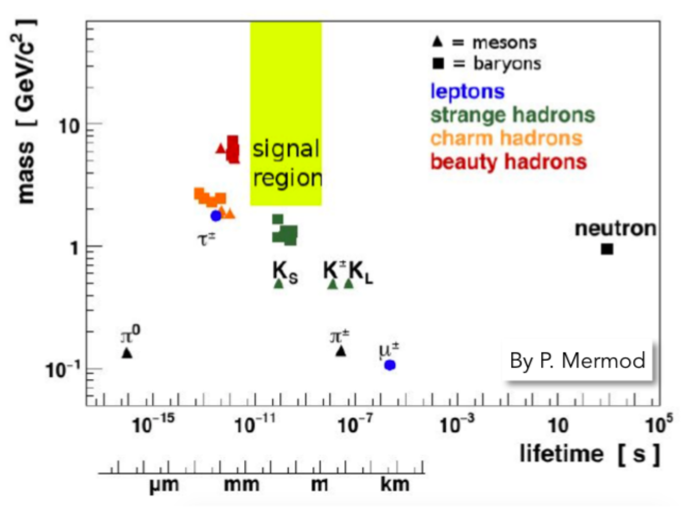


[6]

M(l_2,l_3)

Dispalced vertex analysis ATLAS

[8]



- **Decay in flight of hadrons**
- **Light resonances decays** – Example: boosted B decay into J/Psi or Psi(2S) → dimuon SV with mSV ~ 3 GeV
- **Random crossings of pile-up tracks** Timing and tight ID applied
- **Cosmics producing back-to-back displaced muons**

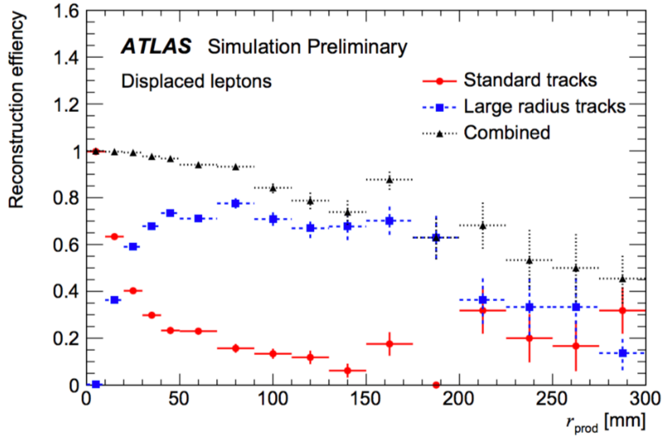
ATLAS: cosmic-ray veto is applied to eliminate high-mass vertices from a single cosmic-ray muon which is reconstructed as two back-to-back muons

- Reconstruction efficiency of displaced tracks, **15%**
  - Dominant systematics in ATLAS search
  - Use sample of K^0_s (select two-pion in invariant mass window 488-508 MeV) (no high-mass DVs)
  - Parameterized
  - From data/MC comparison, extract DV-level weights in bins of r_{DV} and ΣpT
  - Apply those weights to signal MC and check difference in efficiency
- Displaced lepton ID efficiency, **5%**
- uncertainties in the modelling of lepton kinematic distributions and individual decay branching ratios, **10%**
- Prompt-lepton reconstruction and identification, **1%**

Total systematic uncertainty is 24%

ATLAS EXPERIMENT **Large-radius** tracking (**LRT**) algorithm.

- Larger d_0 ~300 mm (wrt standard reconstruction)
- computer-intensive, can be run only on a limited fraction of the RAW data → "filter" selection



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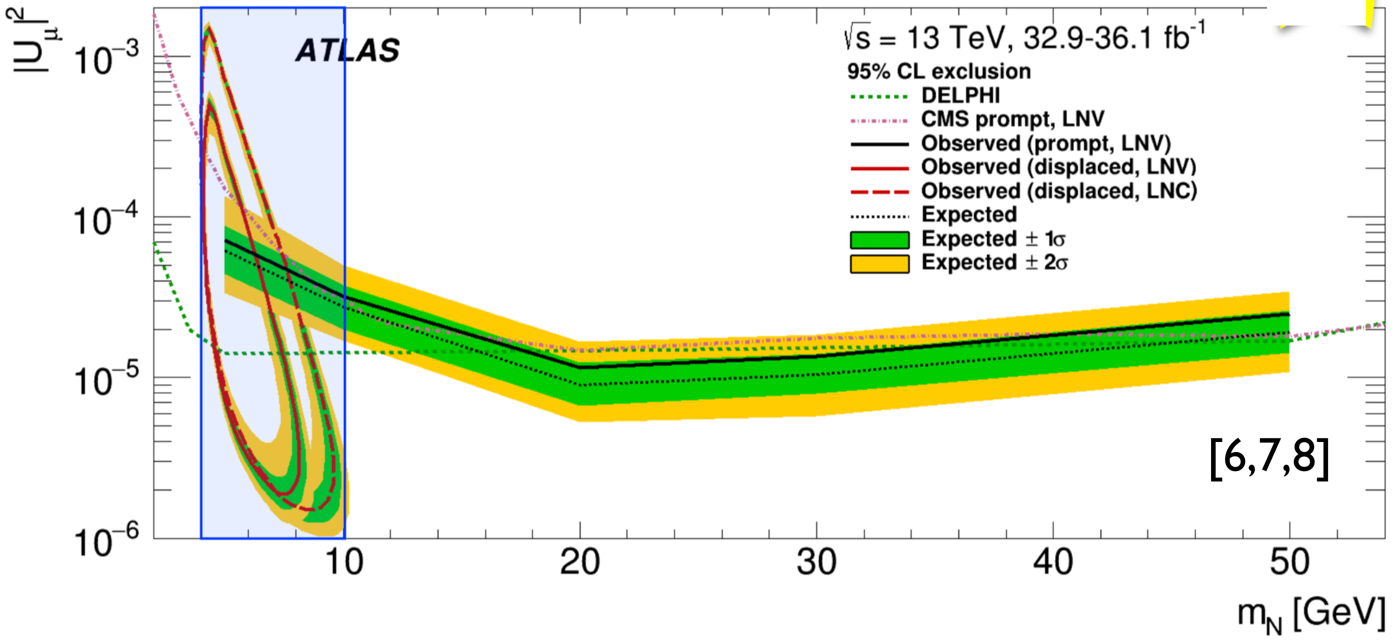
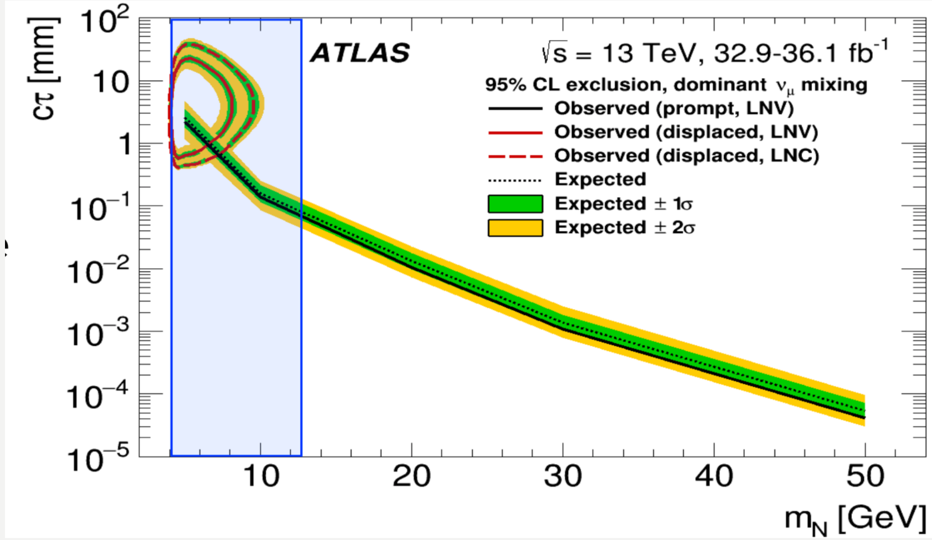
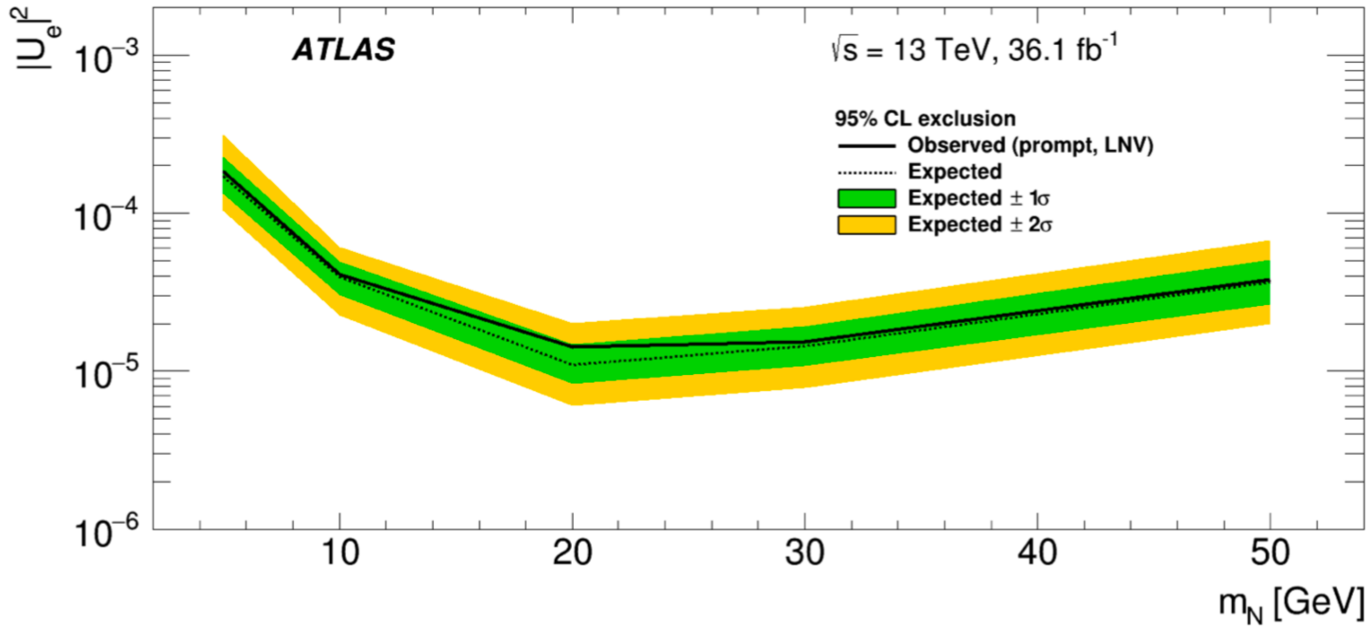


[6,7,8]





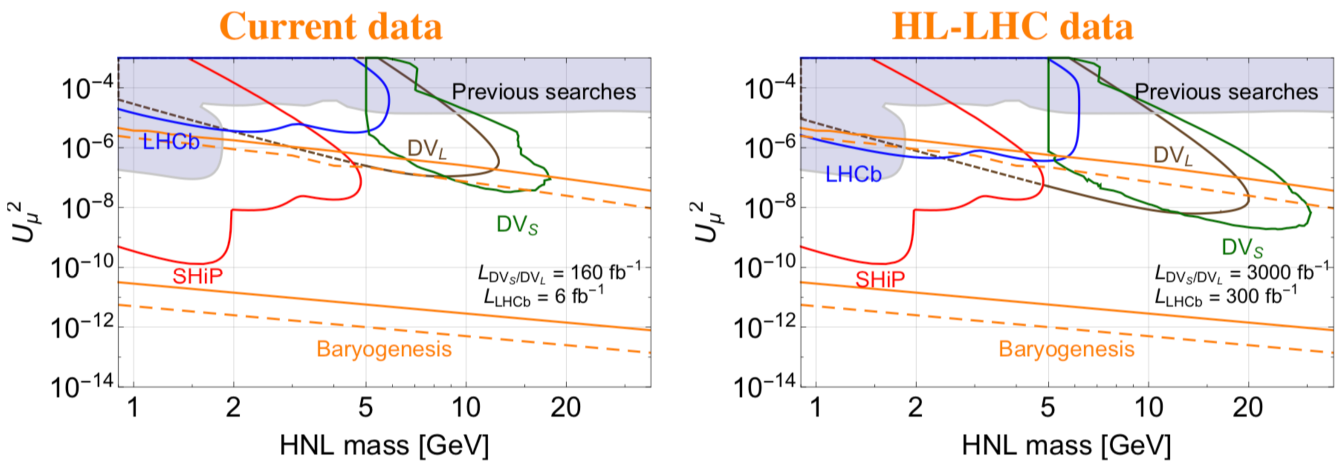
There is a whole program of improvements in plan :

- Add sensitiviy to tau channel
- Interpret data with less simple scenarios for mixing
- Add hadronic channels N decays to the DV analysis
- Explore more triggers and prepare better triggers for Run3, prompt channel
- Improve reconstruction and trigger strategy for DV channel
- Improve analysis , eg [13]

Order of magnitude improvements can be achieved even before HL-LHC

HL-LHC LNV PROSPECT

Phenomenological projections for the LHC



- several recent phenomenological works with projections for displaced HNLs
- a displacement kills SM bkg, signal acceptance estimated with gen-level info:
  - **DV**$_S$: a displaced vertex search in a tracker at ATLAS or CMS
  - **DV**$_L$: a search with muon system at CMS (3 m decay volume)
  - **LHCb reach**: an inclusive HNL search in B decays
- available now data allow to probe parameter space interesting from baryogenesis considerations!

[23]

Boiarska *et al* arXiv:1902.04535

Phenomenological study
Of expectations for LNV
Decays at HL-LHC

Displaced vertices only !

For prompt channel :
- Statistics is essential to improve
- Analysis method is still pretty basic and a NN would probably do a good job if enough stats
- Trigger improvements for HL-LHC should allow to keep low thresholds sensitivity

→ No surprise if we can go down one order of magnitude or more

FCC-EE

Main background

$Z \rightarrow W{\star}W \rightarrow l\nu qq$

-without lifetime, limit on sensitivity down to $U^2=10^{-6}$

-with lifetime, detached vertex helps tremendously in background rejection (basically 0 background)

→ 2×1012 $Z \rightarrow \nu\bar{\nu}$ events → A mixing of $|U|^2 \sim 10^{-12}$

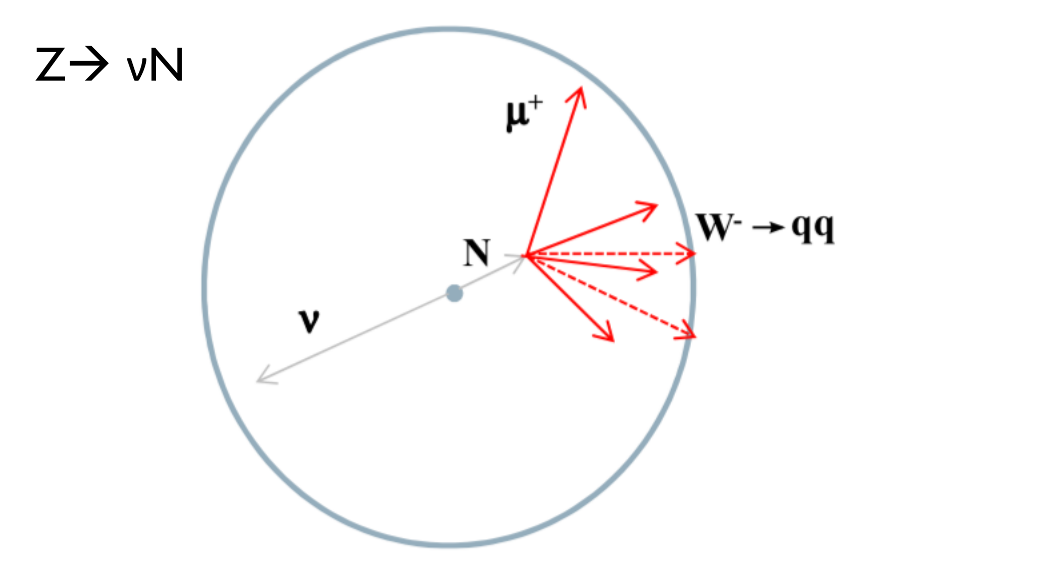
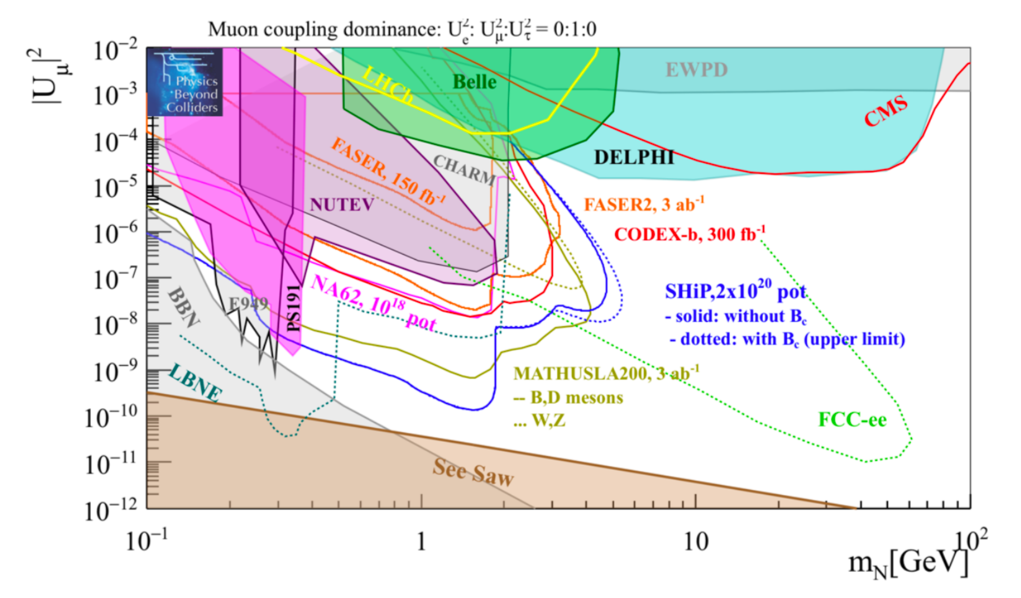
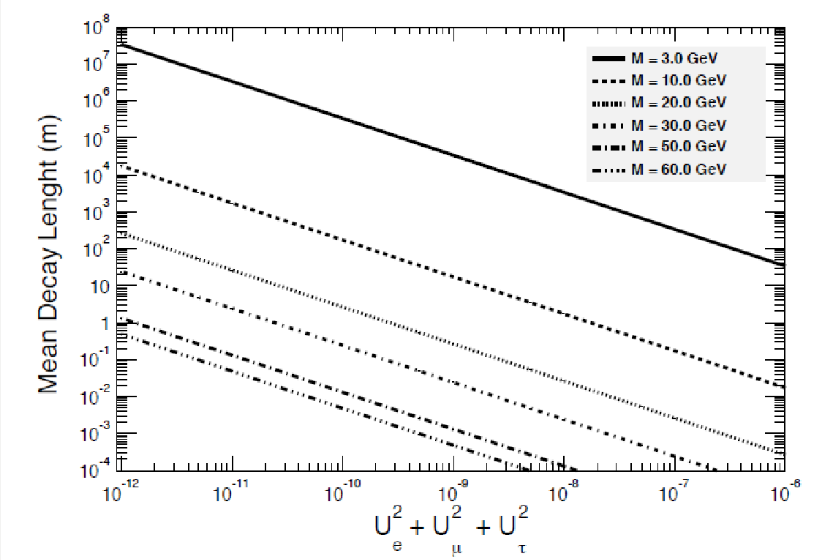


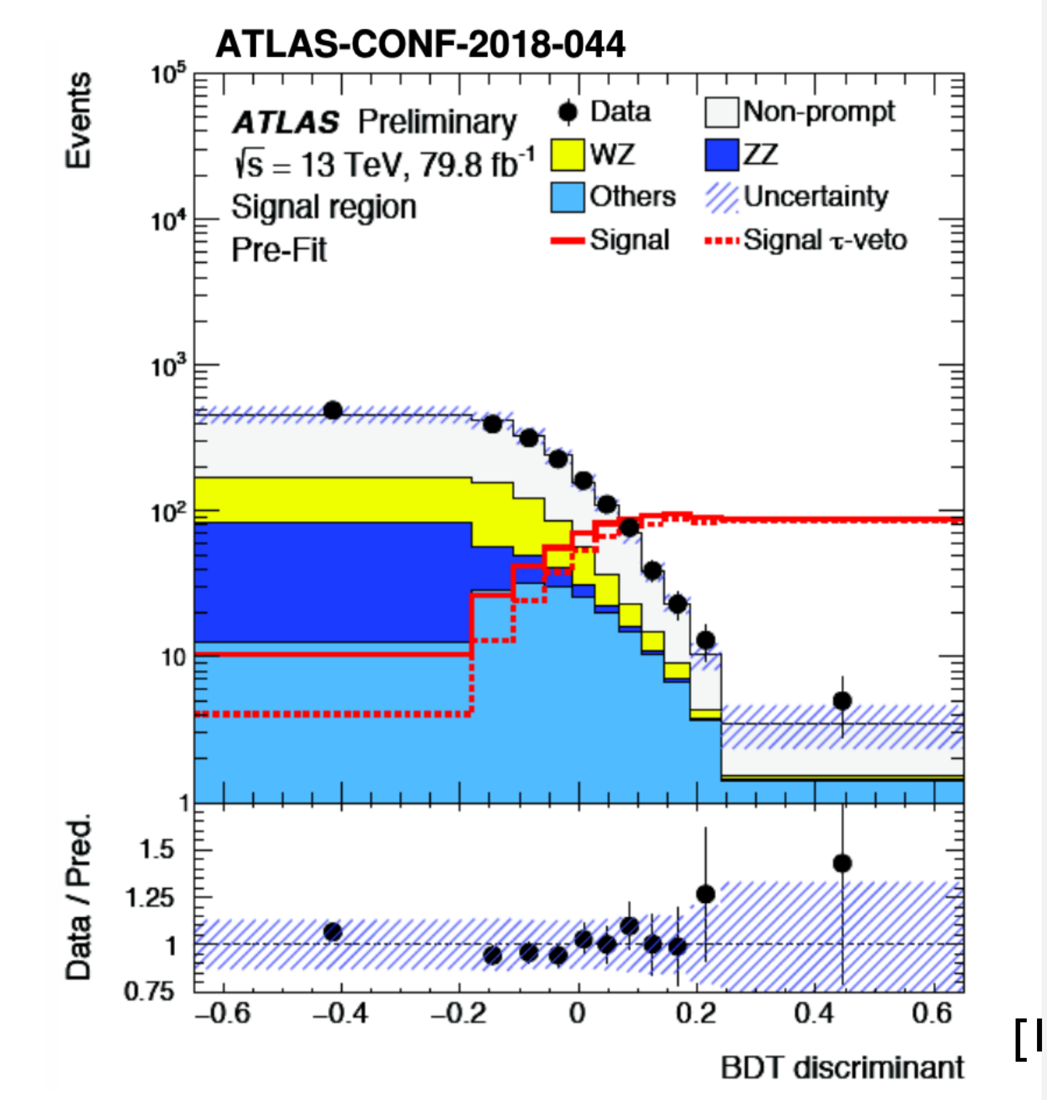
Figure 7: Sketch of the topology of a $Z \rightarrow \nu N$ decay, with N subsequently decaying into $\mu^+ W^-$.



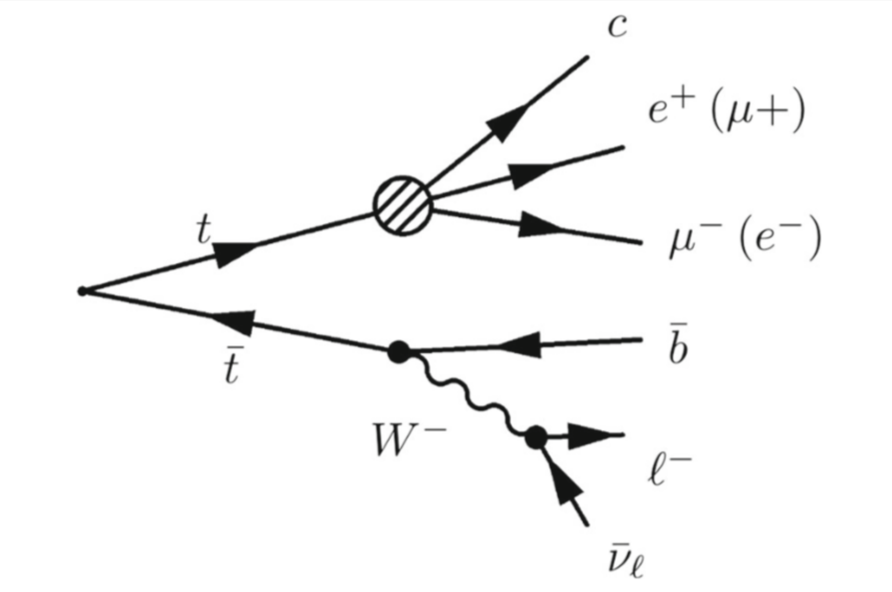


[24]

LFV IN TOP DECAYS



[11]



Search strategy :
3 isolated light leptons
≥ 2 jets, pT > 25 GeV

60% of the background is composed of ttbar and Z+jets events with an extra non-prompt lepton.

A Boosted Decision Tree (BDT) is trained on simulated events.

LFV IN TOP DECAYS

80 fb^{-1} 13 TeV

$$\mathcal{B}(t \to \ell\ell' q) < 1.36^{+0.61}_{-0.37} \times 10^{-5} \quad \text{(expected)}.$$

[11]

$$\mathcal{B}(t \to \ell\ell' q) < 1.86 \times 10^{-5} \quad \text{(observed)}.$$

$$\mathcal{B}(t \to e\mu q) < 4.8^{+2.1}_{-1.4} \times 10^{-6} \quad (\text{no } \tau \text{ in cLFV vertex, expected}),$$

$$\mathcal{B}(t \to e\mu q) < 6.6 \times 10^{-6} \quad (\text{no } \tau \text{ in cLFV vertex, observed}).$$

From phenomenological study : [12]

Table 5 Expected upper limits on $BR(t \to q\mu^{\pm}e^{\mp})$, under the hypothesis of the absence of signal, for 8, 13 TeV (in two scenarios: the case of 20 and 100 fb^{-1} collected luminosity) and 14 TeV for 3000 fb^{-1} collected luminosity

	8 TeV (20 fb^{-1})	13 TeV (20 fb^{-1})	13 TeV (100 fb^{-1})	14 TeV (3000 fb^{-1})
$BR(t \to q\mu^{\pm}e^{\mp})$	$<6.3 \times 10^{-5}$	$<2.9 \times 10^{-5}$	$<1.2 \times 10^{-5}$	$\lesssim 2 \times 10^{-6}$

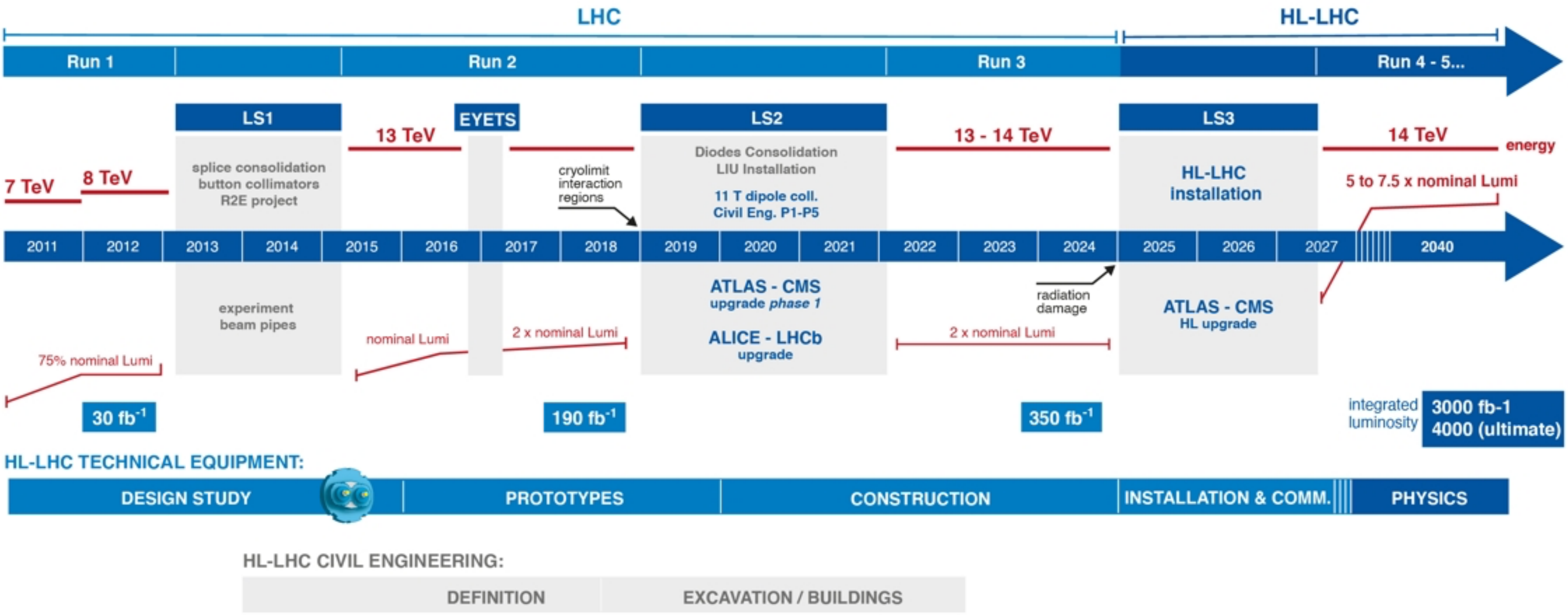
Pretty spot on ! (despite being a study with no systematics)

CONCLUSIONS

- Exciting new era of precision in LFV/LNV tests at EW scale at colliders has started.
- LEP precision is beated in all areas.
- FCC-ee will be the next future project to bring important improvement in precision in these tests.

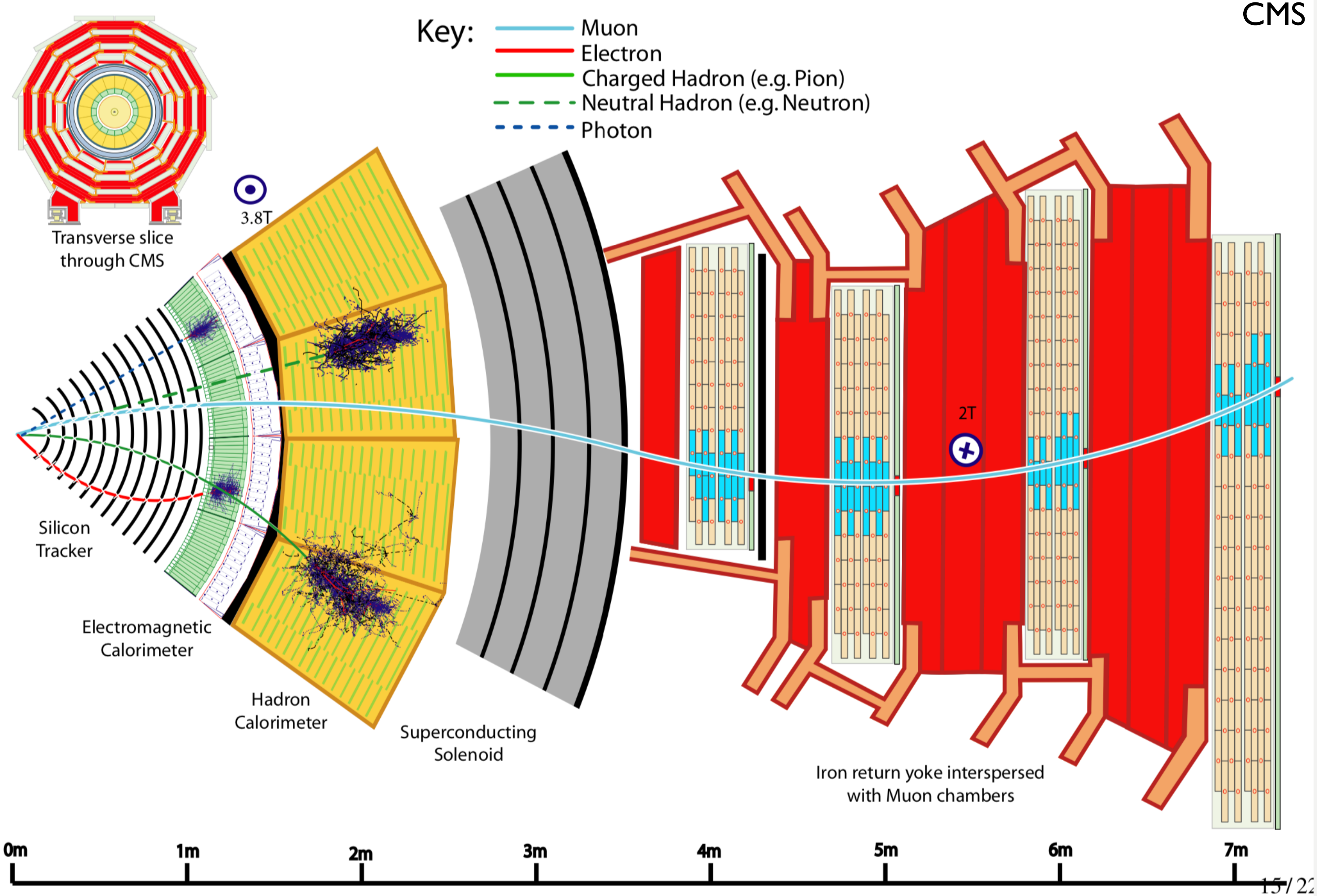
BACKUP

LHC / HL-LHC Plan

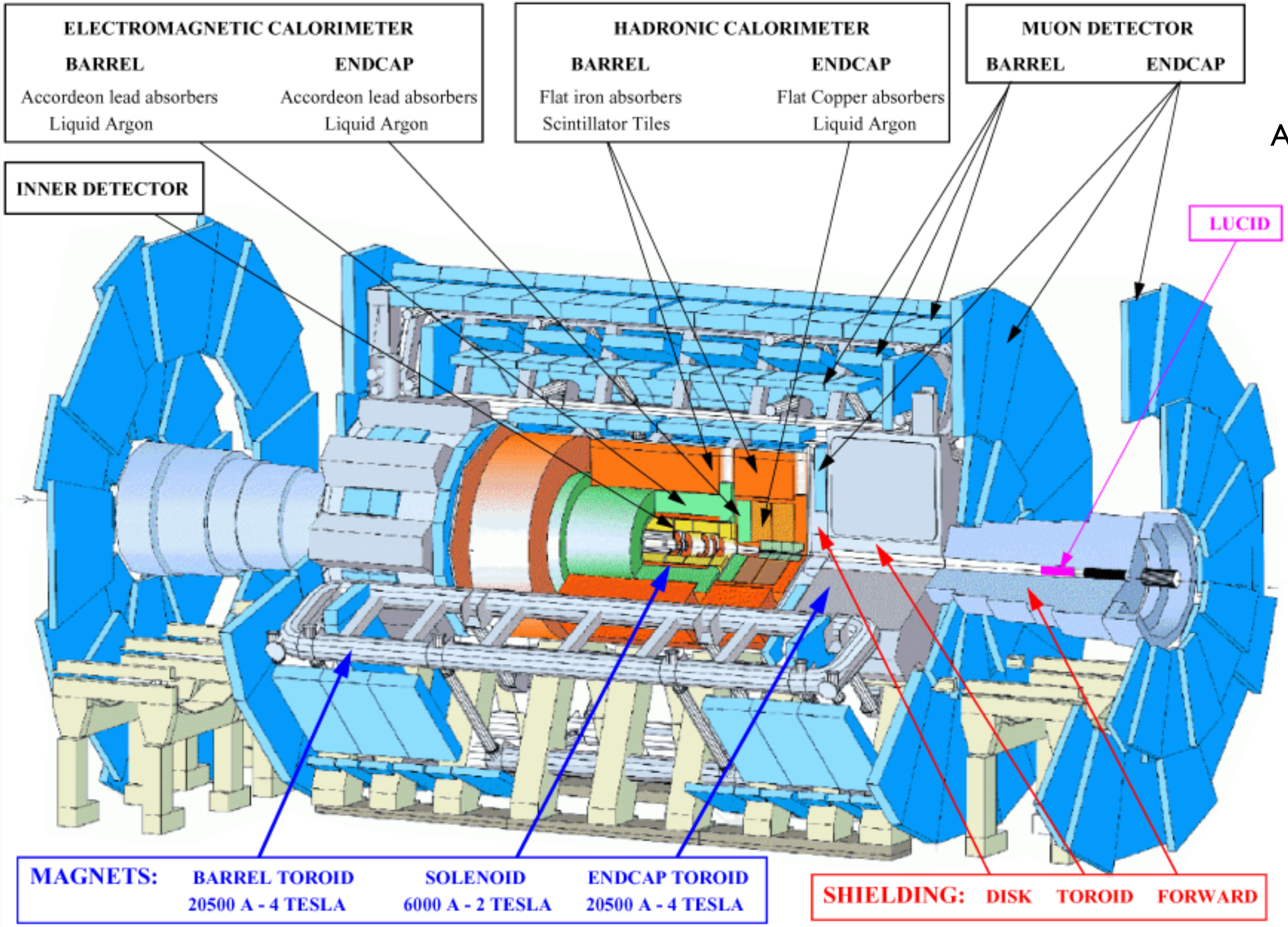


Particles passing through detector

CMS



ATLAS



ELECTROMAGNETIC CALORIMETER
BARREL
Accordeon lead absorbers
Liquid Argon
ENDCAP
Accordeon lead absorbers
Liquid Argon
HADRONIC CALORIMETER
BARREL
Flat iron absorbers
Scintillator Tiles
ENDCAP
Flat Copper absorbers
Liquid Argon
MUON DETECTOR
BARREL
ENDCAP
INNER DETECTOR
LUCID
MAGNETS:
BARREL TOROID
20500 A - 4 TESLA
SOLENOID
6000 A - 2 TESLA
ENDCAP TOROID
20500 A - 4 TESLA
SHIELDING:
DISK
TOROID
FORWARD

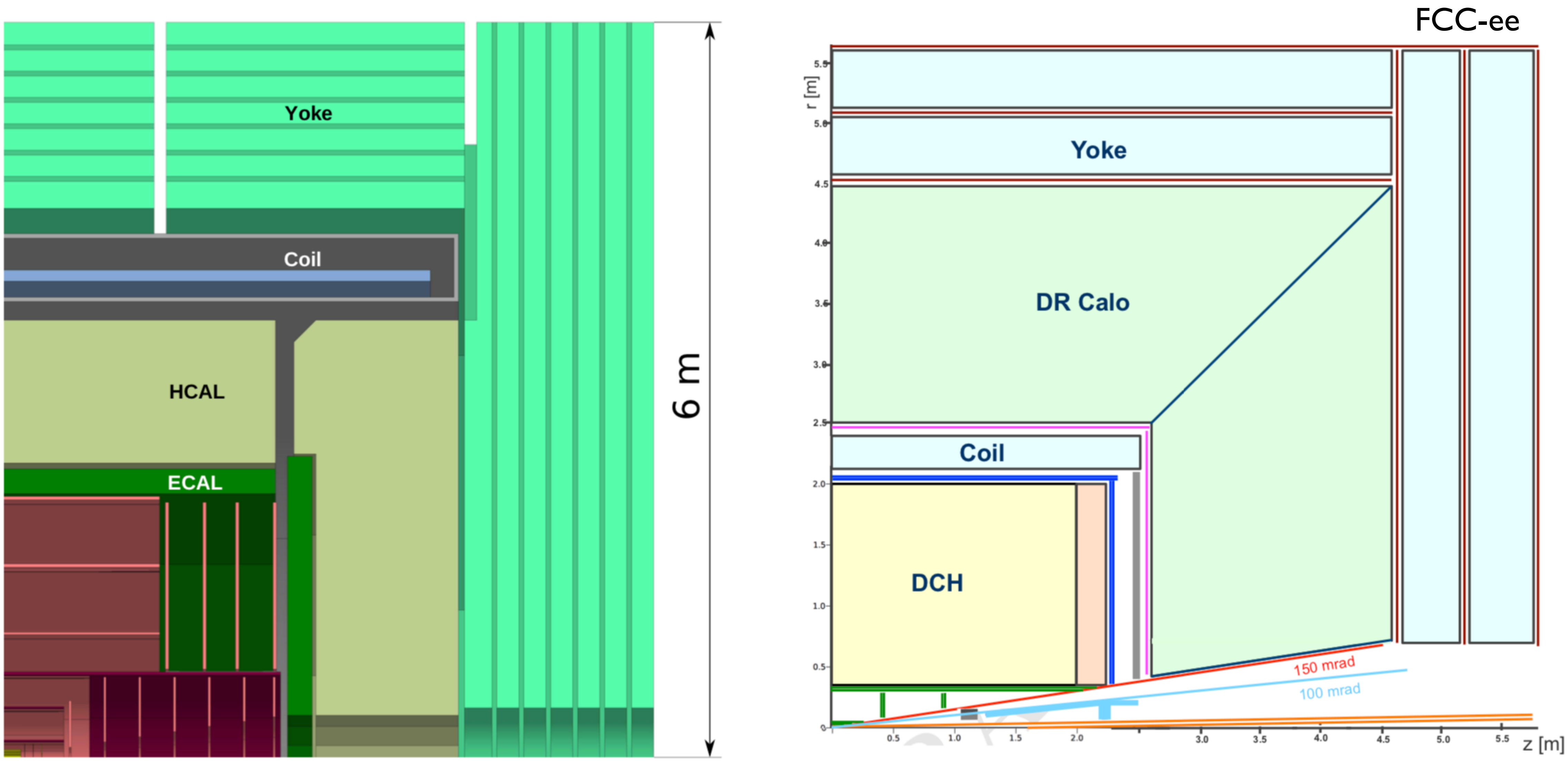
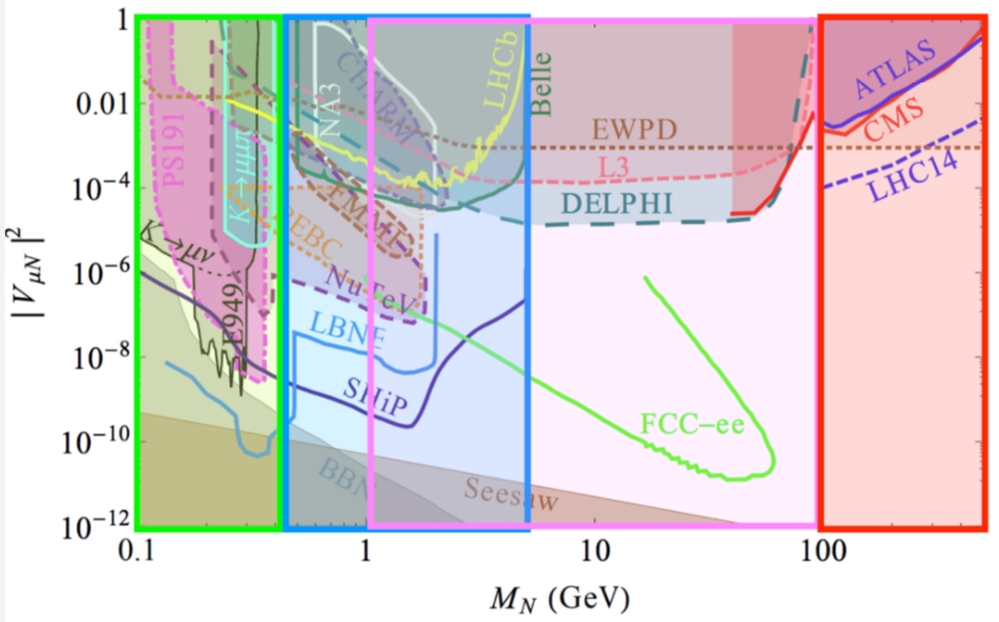


Figure 1: Vertical cross sections showing the top right quadrants of CLD (left) and IDEA (right)

ADDITIONAL NEUTRINOS



- $m_N > m_Z$
- LHC can exceed the limits from electroweak precision data

- $m_N < m_Z$
- Results from LEP ($Z \to \nu N$)
- Currently explored at the LHC (ATLAS, CMS)

- $m_N < m_K$
- Using K decays, such as $K^\pm \to \ell N$, $K^\pm \to \mu\mu\pi$
- E.g. NA62

- $m_N < m_{D,B}$
- Explored at colliders (e.g. Belle, LHC*b*) or beam-dump experiments (e.g. SHiP)

[8]

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